Climate Change and Peak Flows:

Knowledge–to-action to help managers address impacts on streamflow dynamics and aquatic habitat

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Anne Nolin (PI),
College of Earth Ocean and Atmospheric Sciences, Oregon State University

Gordon Grant
USDA Forest Service PNW Research Station

Mohammad Safeeq
Sierra Nevada Research Institute, University of California-Merced

Sarah Lewis, Matt Cooper and Laura Hempel
College of Earth Ocean and Atmospheric Sciences, Oregon State University

1. Administrative:

Anne Nolin, PI
College of Earth, Ocean and Atmospheric Sciences
(541) 737-8051; nolina@geo.oregonstate.edu
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2. Public Summary:

What will the rivers of the Pacific Northwest look like in the future? Will they be stable or unstable? Will the waters be cold and clear or warm and muddy? Will they have salmon or other species? These questions motivated our two-year study of climate warming effects on headwater streams draining the Cascade Mountains. Using a novel combination of snow, geohydrology and sediment transport models we assessed the vulnerability of stream channels to changing peak streamflow. Our snow modeling shows that with just a 2°C warming, snowfall shifts to rainfall at all elevations, peak snowpacks occur over two months earlier, and snowpacks are reduced by over half of historical values. Our geohydrology modeling shows that greater rainfall and earlier snowmelt enhances peak winter streamflows but impacts depend on snow amount and watershed geohydrology. In spring-fed watersheds, increased winter flows are within historical bounds. In runoff-dominated watersheds, increased winter flows will exceed the historical range by up to 44% and the frequency of high flows will increase by over 100 days per year. Since streambed gravels and sand are transported during high flows, climate warming is likely to result in a dramatic increase in the amount of sediment moving through Cascade streams. Daily sediment transport rates in the surface-runoff system could potentially double. Besides affecting water quality with increased levels of suspended sediment, more frequent sediment transport events may lead to instability in the gravels where bull trout and salmon lay their eggs, making their survival less certain in the future. A key aspect of this project was engaging managers through a knowledge-to-action approach. Stakeholder dialogs were held in organized workshops and informal discussions through which we shared needs, information, and knowledge to interpret the consequences of these projected changes for water supply, threatened & endangered aquatic species, and dam operations.

3. Technical Summary:

As climate continues to warm, the Pacific Northwest will see a greater shift from snow to rain and snowpacks melting earlier, both of which are likely to lead to higher winter streamflows. These changes in snow and peak streamflow will vary across the region, and identifying how much change will occur, where, and when, with what effects on ecosystems and human systems, is a key research challenge with many direct management implications. Higher peak flows will mobilize and scour streambed sediments more deeply, destabilize and transport woody debris, modify channel geometry, and damage riparian habitat.

Using a novel convolution of snow dynamics and geohydrology, we assessed the changes in snow, peak flow regimes, and sediment transport for selected watershed in the Oregon Cascades. We engaged with managers in a knowledge-to-action approach to interpret the consequences of these changes for water supply, threatened & endangered aquatic species, and dam operations. Specifically, we conducted an integrated geohydrologic study using paired watersheds in the Oregon Cascades to answer these questions: 1) How will peak streamflows change in response to the pattern of diminishing snowpacks interacting with spring-fed vs. runoff-dominated watersheds?; 2) What are the consequences of changing peak flow regimes to sediment transport, channel stability and morphology, and how might these changes affect water quality and aquatic habitat?, 3) What are the implications to downstream water supply and dam operation?

To answer these questions we identified four overarching goals:

1. *Model the watersheds*. Study changes in snow and peak streamflow in paired watersheds spanning a range of climate scenarios and geohydrology characteristics, using physically based, validated models that specifically capture salient dynamics of coupled snow-surface-groundwater-vegetation hydrologic systems;
2. *Explain interactions*. Identify and quantify the linkages and feedbacks among hydrologic and geomorphological aspects of peak flows;
3. *Identify vulnerabilities*. Determine how/where the combination of watershed characteristics and climate change will negatively impact water quality (including stream temperatures), extreme events, and aquatic habitat for key threatened & endangered species;
4. *Implement a knowledge-to-action approach*. Collectively and collaboratively engage researchers and stakeholders in the process of information transfer through dialog and decision support tools.

We successfully met all aspects of goals 1-2 and most aspects of goals 3 & 4. For goal 3, we were not able to address the effect of changing peak flows on stream temperatures and we did not specifically model the impacts on aquatic habitat. For goal 4, we were not able to update the visualization tool.

In addition to meeting most of our goals, we also developed a new approach for modeling snow hydrology in a data sparse region (the east side of the Cascades). We developed a bias-correction method for climate data that were used as input to our snow model. This method was highly successful in increasing the overall accuracy of the model. Moreover, the method has important applications for snow and hydrologic modeling outside of this study. It can be applied to gridded data anywhere in the US for a wide range of purposes.

As evidenced in Sections 5-7, the project was highly successful with substantial scientific results and strong integration with managers throughout the process.

Summary of Modeling Results:
Our snow modeling results show that with just a 2°C increase in winter temperatures, winter precipitation shifts from snow to rain and snowpacks melt earlier. At elevations below approximately 1100 m, there is a 70% increase in rainfall (decrease in snowfall) and even at elevations above 2500 m there is a 10-20% increase in rainfall. The timing of peak SWE changes dramatically with a 2°C warming. In several of the sub-basins, the date of peak SWE occurs by as much as 63 days earlier on the east side of the Cascades and over 70 days on the west side, effectively reaching a maximum in January and gradually melting throughout winter when historically, snowpacks would have continued to grow until late March/early April. Snow modeling results show a 54% reduction in average April 1 SWE for the west side McKenzie basin under a 2°C warming scenario and a 60% reduction for the east side Metolius basin.

Results from the geohydrology simulations show that the initial 2°C warming will have the greatest impact (percent change) on peak streamflow regimes across all the watersheds. There are enhanced peak flows for all watersheds under both the 2°C and 4°C warming scenarios but the magnitude of increase varies by the amount of snow in the watershed and the overall groundwater contribution. In spring-fed watersheds, the increase in winter flows under 2°C and 4°C warming scenarios are within the historical range of spring snowmelt peak flows. In runoff-dominated watersheds the increase in winter flows will exceed the historical streamflow range by as much as 44%. Annual maximum daily peak flows are likely to increase by as much as 35% under warming scenarios (+2°C and +4°C) and as much as 55% under the +4°C with +10% precipitation scenario. Compared to the west side of the Oregon Cascades, annual daily maximum peak flows for the east side basins show a greater sensitivity to the 4°C warming scenario. This can be attributed to colder snowpacks on the eastern slopes of the Oregon Cascades.

Sediment transport modeling results suggest that since most of the gravel and sand on the bed of stream channels is transported during high flows, climate warming and the ensuing higher peak flows will result in a dramatic increase in the amount of sediment moving through Cascade streams. The spring-fed systems will experience somewhat larger peak flows (up to 16% higher) and an increase in the number of days/year with flows greater than historical flows (at least 25% greater) by 67 days. In comparison, even larger changes were observed in the surface-runoff systems. For those basins, the highest flows will increase up to 85% and the number of days in a year with flows greater historical flows (at least 25% greater) will increase by 135 days. Consequently, daily sediment transport rates in the surface-runoff system will be up to 200% greater than baseline conditions under warming scenarios compared to only about 60% greater in the spring-fed system. Increased sediment transport in the surface runoff system occurs during the entire year, rather than just the winter flood season. Besides effecting water quality with increased levels of suspended sediment, the higher frequency of sediment transport events could lead to instability in the gravels where bull trout and salmon lay their eggs, making their survival less certain in the future.

These changes have major management implications: these streams are currently the source for the coldest, clearest water, the best aquatic habitat for coldwater species such as bull trout, and provide most of the summer streamflow in many major river systems (e.g., Willamette, Deschutes, Klamath, Rogue, Sacramento). We know of no other fluvial system and associated infrastructure in the U.S. that is potentially as vulnerable to a change in winter flow regime as these critical spring-fed watersheds.

4. Purpose and Objectives:

The original objectives included the four goals listed below:

1. *Model the watersheds*. Study changes in snow and peak streamflow in paired watersheds spanning a range of climate scenarios and geohydrology characteristics, using physically based, validated models that specifically capture salient dynamics of coupled snow-surface-groundwater-vegetation hydrologic systems;
2. *Explain interactions*. Identify and quantify the linkages and feedbacks among hydrologic and geomorphological aspects of peak flows;
3. *Identify vulnerabilities*. Determine how/where the combination of watershed characteristics and climate change will negatively impact water quality (including stream temperatures), extreme events, and aquatic habitat for key threatened & endangered species;
4. *Implement a knowledge-to-action approach*. Collectively and collaboratively engage researchers and stakeholders in the process of information transfer through dialog and decision support tools.

Our study focused on integrating results for selected watershed on the western "wet side" of the Oregon Cascades, exploring the implications for channel stability and water management. We also sought to expand these techniques to the eastern "dry side" of the Oregon Cascades. While we can comprehensively discuss local and regional implications as originally intended, modifications of some of our methods and results reflect challenges met and overcome during the project. Meteorologic and hydrologic data scarcity on the east side required additional, unanticipated analysis to prepare data for modeling input; and key data parameter requirements varied significantly between the two main models, increasing the time needed to complete the integrated analysis for the east side. Our geomorphic channel modeling was scaled back from a two-dimensional to one-dimensional sediment transport model. Stream profile and sediment measurements provided the critical data for the one-dimensional sediment transport model. Results presented here are robust and provide key parameters needed to interpret potential geomorphic change.

We were unable to update the data visualization tool. However, we had highly productive discussions with management colleagues throughout the study. These stakeholders were more interested in having us focus on the integrated modeling work and obtaining sediment transport estimates rather than stream temperature estimates.

5. Organization and Approach:

This section describes the project study area and sample watersheds. In Section 6 we describe the methods and results for each of our distinct modeling efforts: (a) Snow Modeling, (b) Geohydrologic Modeling, and (c) Geomorphic Surveys and Sediment

Transport Modeling. Section 7 provides a synthesis of our main findings, how they should be interpreted for management use, and directions for future research.

a. Description of the Study Watersheds

The spatial and temporal patterns of snow accumulation and melt vary with air temperature, precipitation, topography, and vegetation. Discharge regimes are additionally governed by the drainage efficiency of the underlying geology. We identified eight paired watersheds located on the east (Metolius and Deschutes River) and west (McKenzie River) sides of the Cascades, representing dry and wet climatic regimes, respectively (Figure 1, Table 1). The tributaries of these two rivers are composed of contrasting hydrologic regimes: surface-runoff dominated Western Cascades and deep-groundwater dominated High Cascades systems. Lookout Creek in the HJ Andrews Experimental Watershed (HJA), Boulder Creek (BC), Jefferson Creek near Camp Sherman (JCNCS), and Canyon Creek near National Forest Road 1234 (CCNN1234) represent the runoff-dominated streams. Whereas, Mckenzie River at the Clear Lake (McKCLR), Anderson Creek (AC), Shitike Creek near Warm Springs (SCNWS), and Jack Creek near National Forest Road 1234 (JCNNF1234) represent spring-fed streams. The drainage areas of these watersheds range from 1 to 238 km^2 on west side and from 21 to 72 km^2 on east side (Table 1).

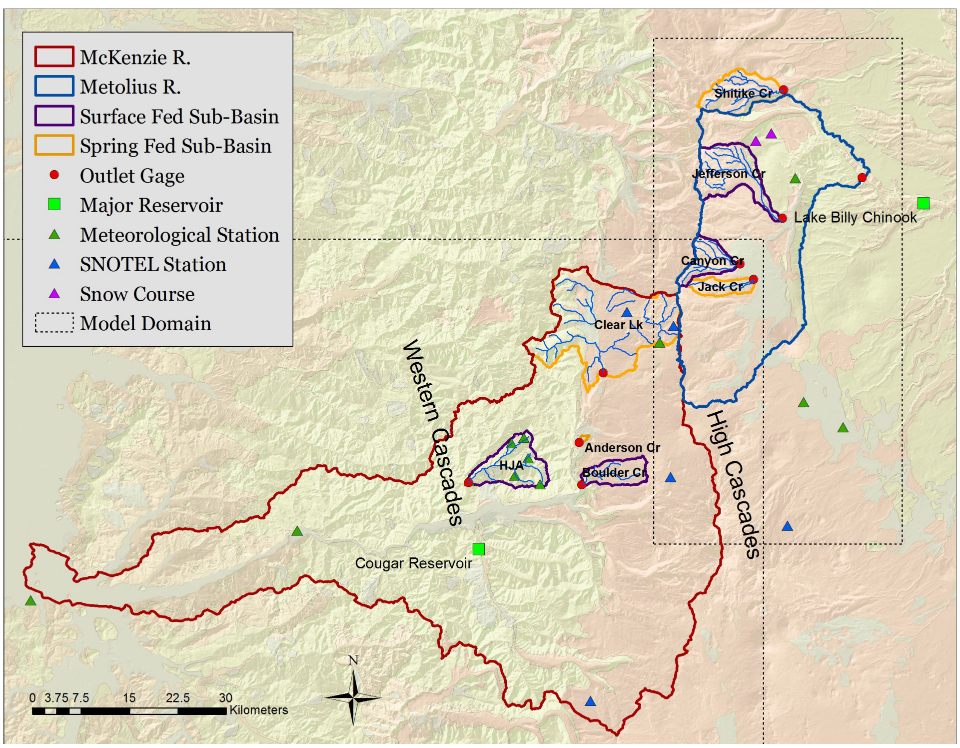

Figure 1. Map of the study watersheds and the modeling domain.

Table 1. Characteristics of the study watersheds.

	Name	Type	Area	Minimum	Mean	Maximum

			(km^2)	elevation (m)	elevation (m)	elevation (m)
West side	Lookout	SW	62	437	942	1621
	Boulder	SW	33	538	1191	1856
	Clear	GW	238	918	1318	2027
	Anderson	GW	1	632	691	3146
East side	Jefferson	SW	73	855	1443	3090
	Canyon	SW	34	1016	1503	2299
	Shitike	GW	58	1098	1484	2106
	Jack	GW	22	938	1295	2039

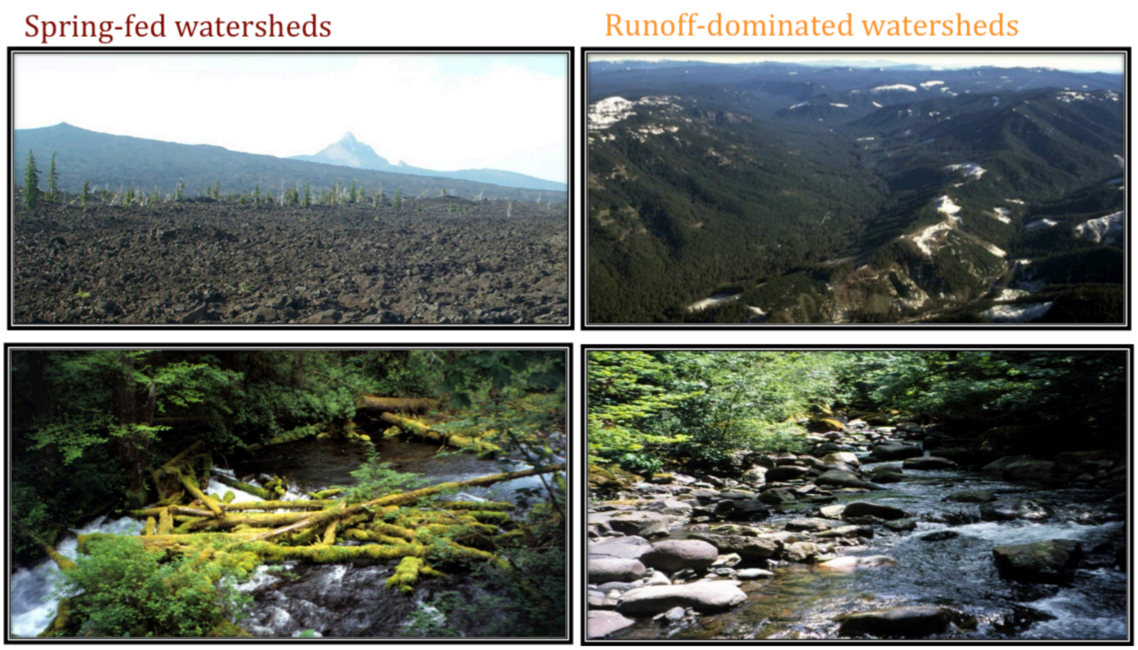

Figure 2. Contrasting spring-fed and runoff-dominated streams.

6. Methods and Results for Each Modeling Task:

b. Snow Modeling

We extended existing modeling in the Cascades western wet-side McKenzie River Basin (Sproles, 2012) to model the spatial distribution of snow water equivalent (SWE) sensitivity to climate warming in the eastern dry-side Metolius and Shitike watersheds using SnowModel (Liston and Elder, 2006). It was found that SWE sensitivity to climate warming differs between the east and west side across elevation zones, within sub-basins, and basin-wide. The east-side modeled sensitivity was less than the west side for elevations below approximately 1300 m and greater than the west side for elevations from about 1300-1900 m. Above about 1900 m, modeled SWE sensitivity is similar on each side. The mechanisms of this difference are not fully elucidated by our methodology but our results provide compelling evidence that these mechanisms deserve further investigation.

Model description

SnowModel (Liston and Elder, 2006) is a physically based snow accumulation and energy-balance snowmelt model. The model is run on a daily time-step and 100-m grid spacing with boundary conditions specified by a digital elevation model and land cover definitions for each grid cell. The model requires input temperature, precipitation, wind direction, wind speed, and relative humidity be defined for every grid cell and every time-step. Incoming radiation and surface pressure are computed from these variables and the boundary conditions and the resulting meteorological surfaces are used to compute snow accumulation and ablation for each grid cell and each time-step. For the input temperature, precipitation, and humidity data we use a gridded meteorological forcing dataset (Livneh et al. 2013) at $1/16^{o}$ spatial resolution. Temperature and precipitation were bias-corrected with PRISM monthly time-series. Wind direction and speed was obtained from the NCEP/NCAR reanalysis product.

Changes to Methodology and Related Results

A decision was made to use a gridded meteorological data product from the Climate Impacts Group (UW) as input to our east side models (Livneh et al. 2013). This dataset is widely used by US land management agencies for model based water resource climate change assessments and thus the choice to use this data contributes to the broad relevance of our results. This also allowed us to use the limited station observations in the east side basins for independent model evaluation. The gridded data was evaluated against the stations in the area and against the PRISM monthly averages. In both cases, a seasonal and elevation-dependent negative bias was found in the gridded temperature and precipitation (Figure 3). We diagnosed the bias by computing regional temperature-elevation and precipitation-elevation gradients (lapse rates) from station data and found that the assumption of temporal and spatial stationarity of lapse rates used to create the gridded data product was responsible for the bias. This finding supports results from other recent investigations but we are the first to directly diagnose the bias. The systematic bias was removed from the gridded data, using PRISM as the reference data. The regional lapse rates were used to downscale the coarse-resolution gridded climate data to the 100-m scale. After correction we found significant improvement in both temperature and precipitation, as evaluated against the station observations (Figure 3). To our knowledge this is the first time that a methodology to downscale this gridded climate data product for a high-resolution hydrologic modeling application has been presented.

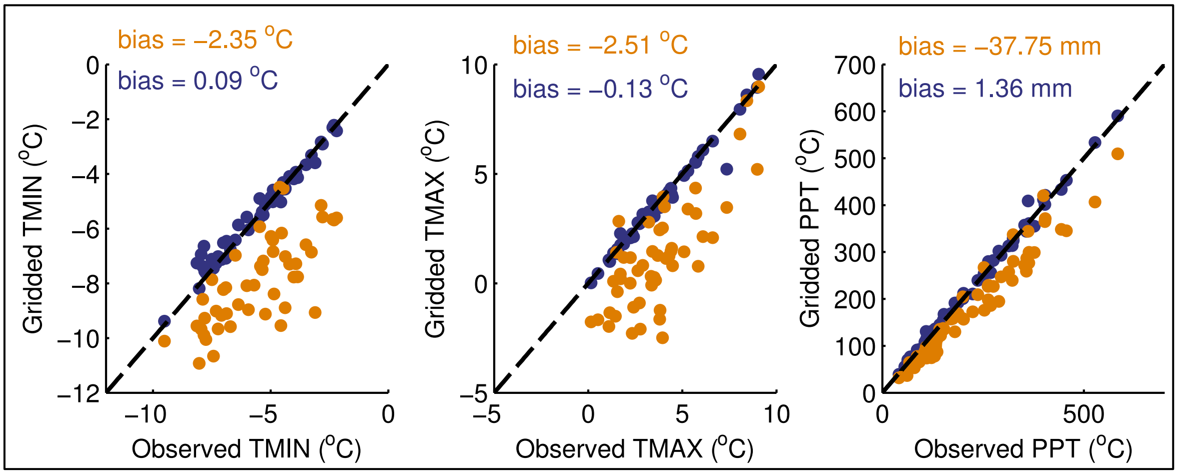

Figure 3. Pre-and post bias corrected winter-time (DJF) minimum and maximum temperature and precipitation compared to observations from stations in the study region.

Although bias-correction significantly improved modeled SWE, large model errors persisted post-correction (Figure 4, top row, dotted blue line). We found that model parameters were not transferable between the west- and east side. Therefore, a parameter estimation experiment was necessary to achieve accurate snow model results for the east side. Because direct observations of radiative fluxes were unavailable on the east side, we chose to use the available SWE measurements as a calibration dataset and optimized the model parameters that control the energy balance of the snowpack to produce the best fit between modeled and measured SWE. This required significant computational effort but was successful in identifying model parameter bias. Optimal parameter estimates were used to model the east side SWE with high accuracy (Figure 4 top row, solid blue line). Modeled vs. measured Nash-Sutcliffe Efficiency for the 1989-2011 period ranged from 0.47 – 0.98 with 18 of 23 years scoring higher than 0.80 (Figure 4 bottom). Together with the bias-correction and lapse rate downscaling methodology, this provides a comprehensive and transferable methodology for modeling snow hydrology in data-sparse regions of the US. Further, we evaluated the impact of this methodology on the modeled SWE sensitivity to climate warming. An evaluation of this type has not been presented in the literature. However, these changes to methodology also significantly extended the time necessary to complete the snow modeling.

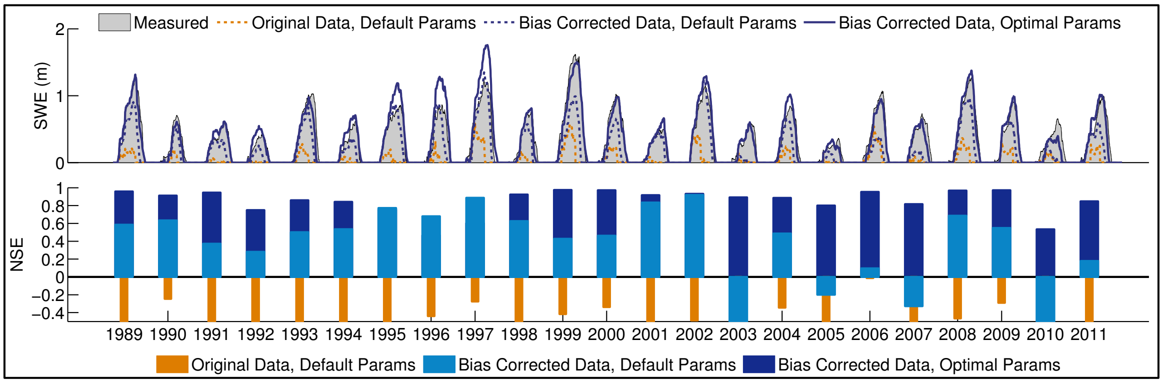

Figure 4. The effect of bias-correction and parameter estimation on modeled SWE. Top row: Measured vs. modeled SWE averaged across the three SNOTEL stations within the east-side modeling domain. Bottom row: the average Nash-Sutcliffe efficiency for the simulations shown in the top row.

Effects of future climate scenarios on modeled SWE

Our results indicate that the relative peak SWE sensitivity (percent decline from a 2°C warming relative to historic conditions) differs on either side of the Cascades in the study region but the difference depends on elevation. Below approximately 1100 m, there is a 70% increase in rainfall (decrease in snowfall) due to a 2°C warming (Figure 6). Even at elevations above 2500 m there is a 10-20% increase in rainfall (decrease in snowfall).

The timing of peak SWE changes dramatically with a 2°C warming. In several of the sub-basins, the date of peak SWE occurs by as much as 63 days earlier on the east side and over 70 days on the west side, effectively peaking in January and gradually melting throughout winter when historical snowpacks would have continued to grow. Figure 7 shows the shift in timing for the date of peak SWE for both the Metolius and McKenzie basins, with the greatest shift occurring in the mid-range of elevations for both basins. Peak SWE timing occurs at least one month earlier for 1000-1500 m in the McKenzie and 1200-2000 m in the Metolius basins.

Differences between the two sides of the Cascades are also evident in terms of the sensitivity of peak SWE magnitude to increased temperature. Below approximately1300 m the west side modeled sensitivity is up to 36% larger than the east side. In the elevation range 1300 – 1900 m, the east side modeled sensitivity is up to 24% larger than the west side. The increase in sensitivity between 1300 and 1900 m on the east side appears to be related to the warmer temperatures on the east side in this elevation range (Figure 8). In this elevation range mean winter air temperature with a 2°C warming is above 0°C on the east side but below 0°C on the west side. Diagnosing the exact mechanisms of the difference in sensitivity on either side of the range across all elevations was beyond the scope of this study but may be related to the relative complexity of the terrain in either watershed (e.g. the distribution of north vs. south facing slopes), the density of vegetation, model-simulated incoming radiation, humidity, and wind speed differences on either side of the range.

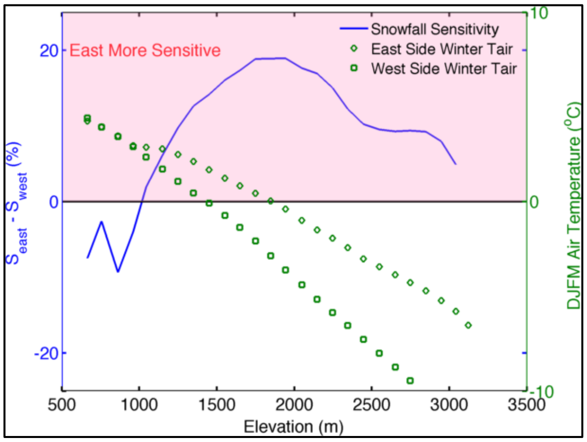

Figure 5. The difference in the percent shift from snow to rain on the east side vs. the west side of the Cascades study region. Shifts from snow to rain are up to 20% greater on the east side than the west side above 1100 m. In this range, mean winter air temperature is warmer on the east side and is above the melting point at elevations up to 1900 m with a 2°C warming.

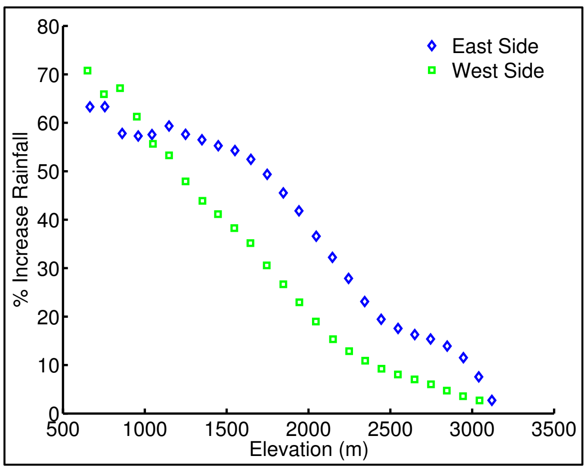

Figure 6. Percent increase in rainfall in the Metolius (east side) and McKenzie (west side) basins vs. elevation with a 2°C warming.

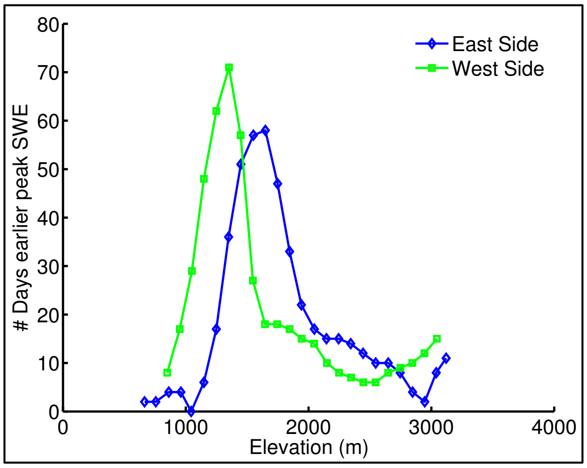

Figure 7. The shift to earlier peak SWE in the Metolius (east side) and McKenzie (west side) basins vs. elevation.

Integrated basin-wide sensitivity is similar on either side of the range but slightly larger on the east side. We observe a 54% reduction in average April 1 SWE for the west side McKenzie basin under a 2^{o}C warming scenario (Figure 8a,b) and a 60% reduction for the east side Metolius basin (Figure 8c,d). Similarly, integrated sensitivity at the sub-basin scale is similar on either side of the range (Figures 9-11). Percent decline in sub-basin spatially integrated peak SWE varies between 50% and 70% (Anderson Cr. is an exception but so little SWE accumulates in this drainage that we omit this statistic). However, the absolute peak SWE loss (Figures 10-11) depends on basin scale so the impact on streamflow will vary with this metric.

That temperature plays the dominant role in driving the sensitivity of SWE to climate change in the Oregon Cascades is demonstrated by the incremental decrease in sensitivity with a 10% increase in precipitation (Figure 9). Results for the west side sub-basins are very similar (not shown).

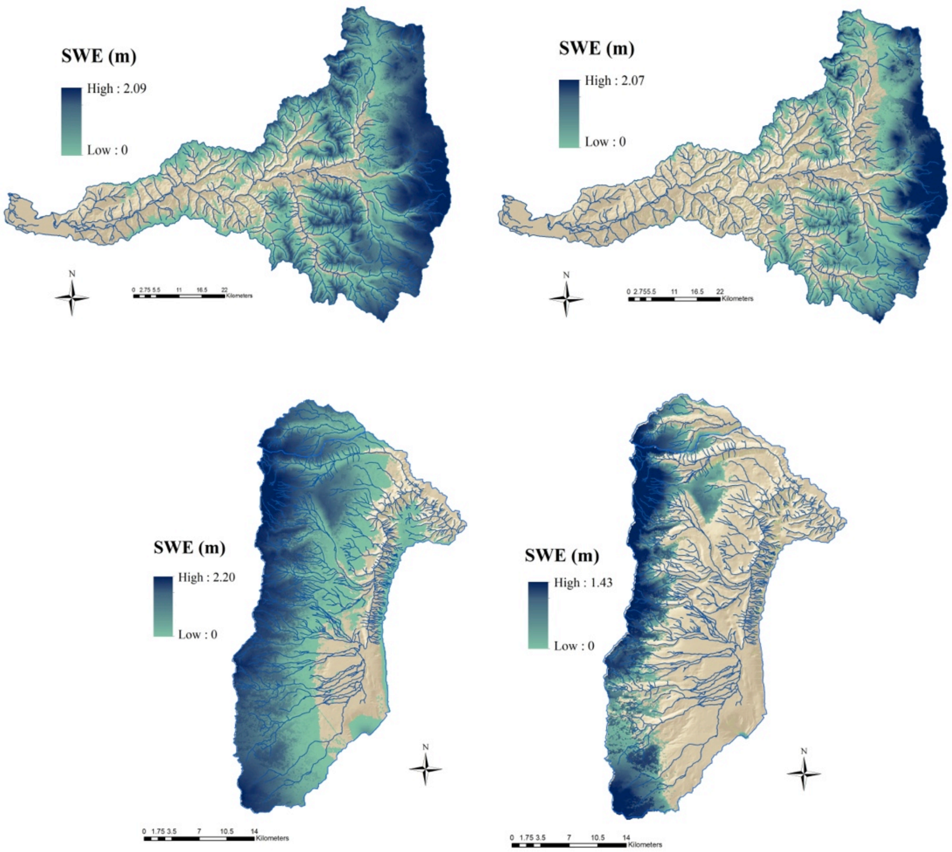

Figure 8. Maps of average April 1 SWE for the west-side McKenzie basin for the (a) reference period and (b) +2°C warming scenario, and for the east-side Metolius (c) reference period and (d) +2°C warming scenario.

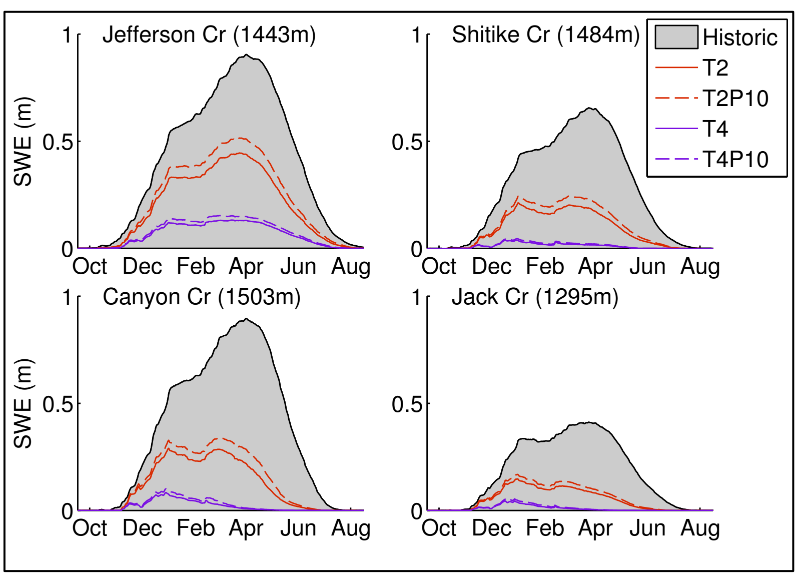

Figure 9. Historic and climate-change scenario basin-integrated SWE for each of the east-side sub-basins for the 2°C (T2) warming, 2°C and +10% precipitation (T2P10), 4°C (T4) and 4°C with +10% precipitation (T4P10).

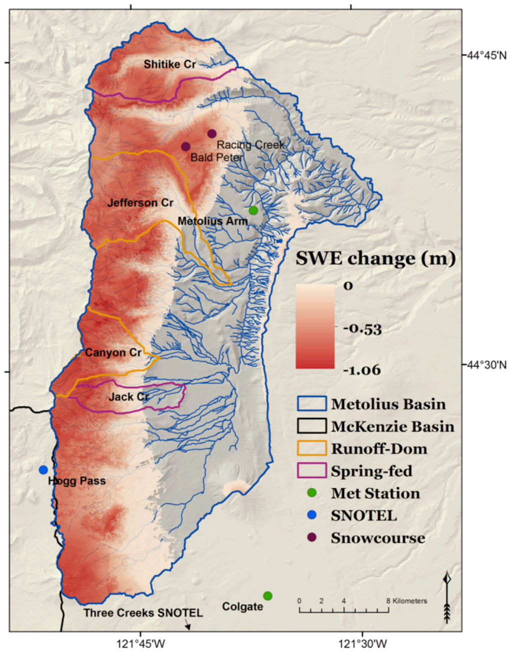

Figure 10. Absolute change in peak SWE for the east-side Metolius and Shitike watersheds for the +2^{o}C warming scenario.

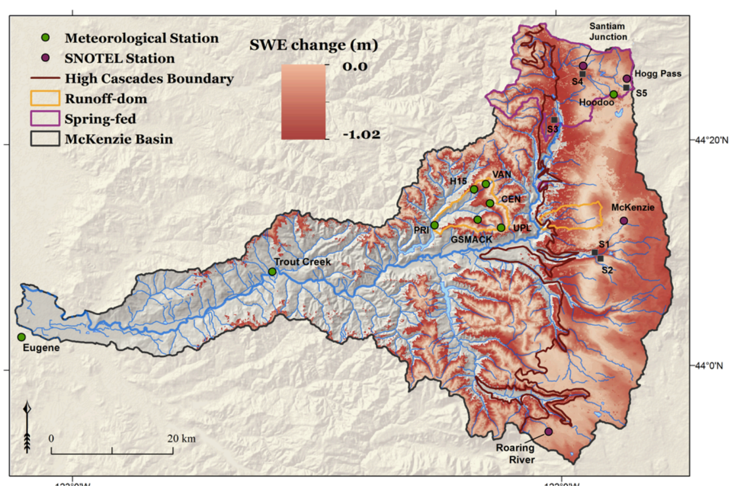

Figure 11. Absolute change in peak SWE for the west side McKenzie basin for the +2^{o}C warming scenario.

Additionally, we tested the impact of bias correction on the modeled SWE sensitivity by optimizing model parameters with each dataset during the historical period and imposing the 2^{o}C warming signal on each dataset. We found that high accuracy can be achieved and the modeled SWE during the reference period is very similar with each dataset. However when a climate warming signal is imposed on the input temperature data the modeled sensitivity with the original data is much smaller than with the bias-corrected data in low- to mid-elevations (Figure 12).

The importance of this second analysis is highlighted by the abundance of available gridded climate data that is used for input to model-based water resource climate change assessments and the arbitrary nature of the data selection process. Here we demonstrate that the choice of gridded input data has a large impact on the modeled climate sensitivity of water resources.

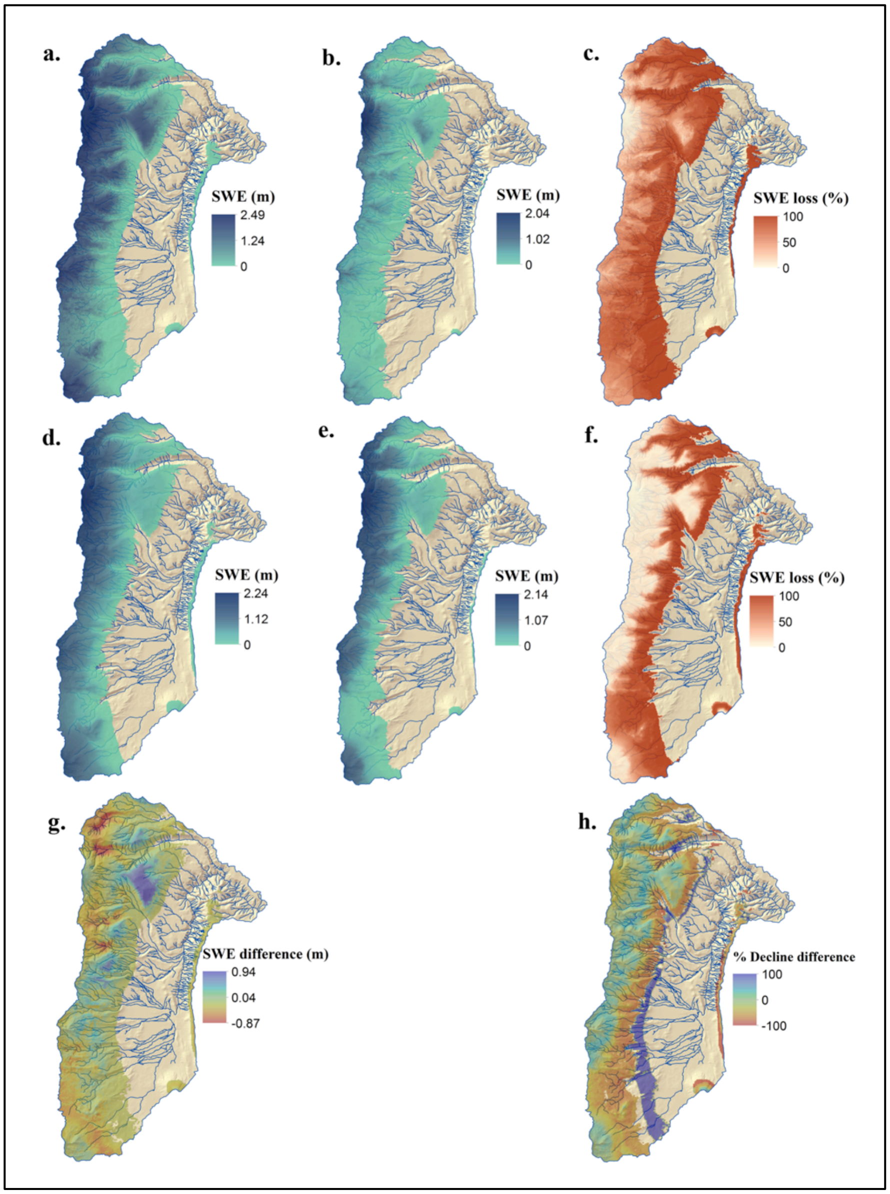

Figure 12. Maps of average peak SWE for the east-side Metolius and Shitike watersheds for the (a) reference period (b) +2°C warming scenario, and (c) percent loss between the reference and +2°C warming scenario with the bias-corrected input data. (d) – (f) same but with original un-corrected data. (g) is the difference in modeled peak SWE between the original and corrected input data during the reference period. (h) is the difference in modeled percent decline in peak SWE between the original and corrected input data for the +2°C warming scenario.

c. Geohydrological Modeling

Model Description

Regional Hydro-Ecological Simulation System (RHESSys) is a physically based and spatially distributed model that simulates hydrological and forest ecosystem processes at a watershed scale (Tague and Band, 2004). A watershed is discretized into similar climate, hydrologic, and ecosystem response units using spatial objects derived from digital elevation model (e.g. hillslopes, watershed and sub-watersheds), climate zones, and size of modeling units or patches (Figure 13). Simulations of hydrological and forest ecosystem processes are typically done at a patch and/or a hillslope scale. The recharge (rain or snowmelt) is distributed between the shallow subsurface and deeper groundwater storage. The shallow subsurface is comprised of: (1) a surface detention store, (2) rooting zone, (3) unsaturated store, and 4) saturated zone store (Tague et al., 2013). The water that bypasses the shallow subsurface is stored in a deeper groundwater bucket and becomes inaccessible to plants. Forest evapotranspiration as well as direct evaporation from litter and bare ground are estimated using the Penman-Monteith approach.

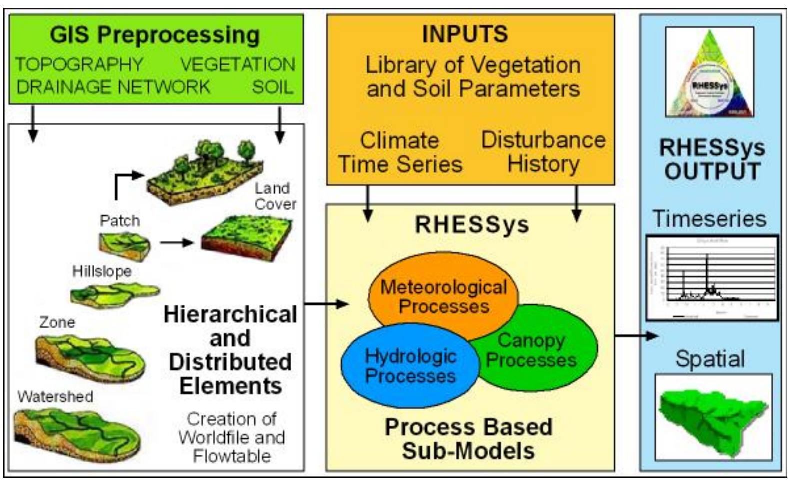

Figure 13. An overview of input data into, internal processing and flow of control within, and derived output for the RHESSys modeling system (source: http://fiesta.bren.ucsb.edu/~rhessys/about/about.html).

The RHESSys model has been extensively applied in the western US and mainly in the Oregon Cascades for evaluating effects of climate change on streamflow and other hydrologic processes (Tague et al., 2008;Tague and Grant, 2009; Garcia et al., 2013; Tague et al., 2013; Garcia and Tague, 2014). Unlike other hydrologic models, RHESSys uniquely captures the importance of deep groundwater contributions to streamflow (Tague et al., 2008) that is vital for modeling streamflow in the Oregon Cascades (Tague et al., 2013).

Model Integration and Calibration

The RHESSys model has its own algorithm to simulate snow water equivalent (SWE) and does not make use of SnowModel simulated spatially distributed SWE in the form of meteorological input. Hence, we had to rely on loose coupling between the two models. We used the spatially distributed maximum, minimum, and average temperatures, relative humidity, rainfall, and snowfall calibrated and validated for SnowModel as climatological input to the RHESSys. The portioning of total precipitation between rainfall and snowfall was performed within the SnowModel using the temperature threshold as described earlier. RHESSys model was calibrated in two steps: 1) iteratively adjusting the temperature melt coefficient (meters of water / ºC) to maximize the Nash-Sutcliffe Efficiency (NSE) between watershed average RHESSys and SnowModel simulated daily SWE; 2) iteratively adjusting the six parameters (*m*, *K*, *po*, *pa*, *gw1*, and *gw2*) to maximize the NSE between observed and RHESSys simulated daily streamflows. The four of the six calibrated parameters (*m*, *K*, *po*, *pa*) in step-2 reflect soil characteristics and shallow subsurface storage and flow paths. The remaining two (*gw1* and *gw2*) parameters characterize deep groundwater contributions to the total streamflow. Observed long-term daily streamflow data were only available for the HJA, McKCLR, SCNWS, and JCNCS. Hence, the step-2 calibrations for streamflow were restricted to these four watersheds. The calibrated parameters were then transferred to other four watersheds based on the climate (east vs. west), geologic characteristics, and flow regime (runoff-dominated vs. spring-fed).

RHESSys Model Calibration and Validation Results

Simulated SWE using SnowModel and RHESSys showed strong agreement with NSE between 0.89-0.96, except for rain dominated AC watershed (Figure 14). Our strategy to only calibrate the temperature melt coefficient worked for west-side watersheds but not for the east-side watersheds where RHESSys simulated SWE were consistently lower than those predicted by the SnowModel (results not shown). This was in part due the fact that the two models treat rain on snow events differently. In SnowModel, if precipitation occurs as rain on an existing snowpack, it is added directly towards the SWE. However, in RHESSys rain over existing snowpack runs through it. To account for this discrepancy, we had to re-adjust the rain-snow temperature threshold for the east-side watersheds.

In contrast to SWE, RHESSys performance in simulating daily streamflow varied significantly between the east- and west-side watersheds (Figure 15). The NSE ranged between 0.40-0.62 for west- and 0.02-0.26 for the east-side watersheds. Similarly, the coefficient of regression between daily observed and simulated streamflows ranged between 0.52-62 for west- and 0.42-0.52 for the east-side watersheds. In general peak flows were largely under-predicted across the entire four calibration watersheds, more so on the east- than the west-side.

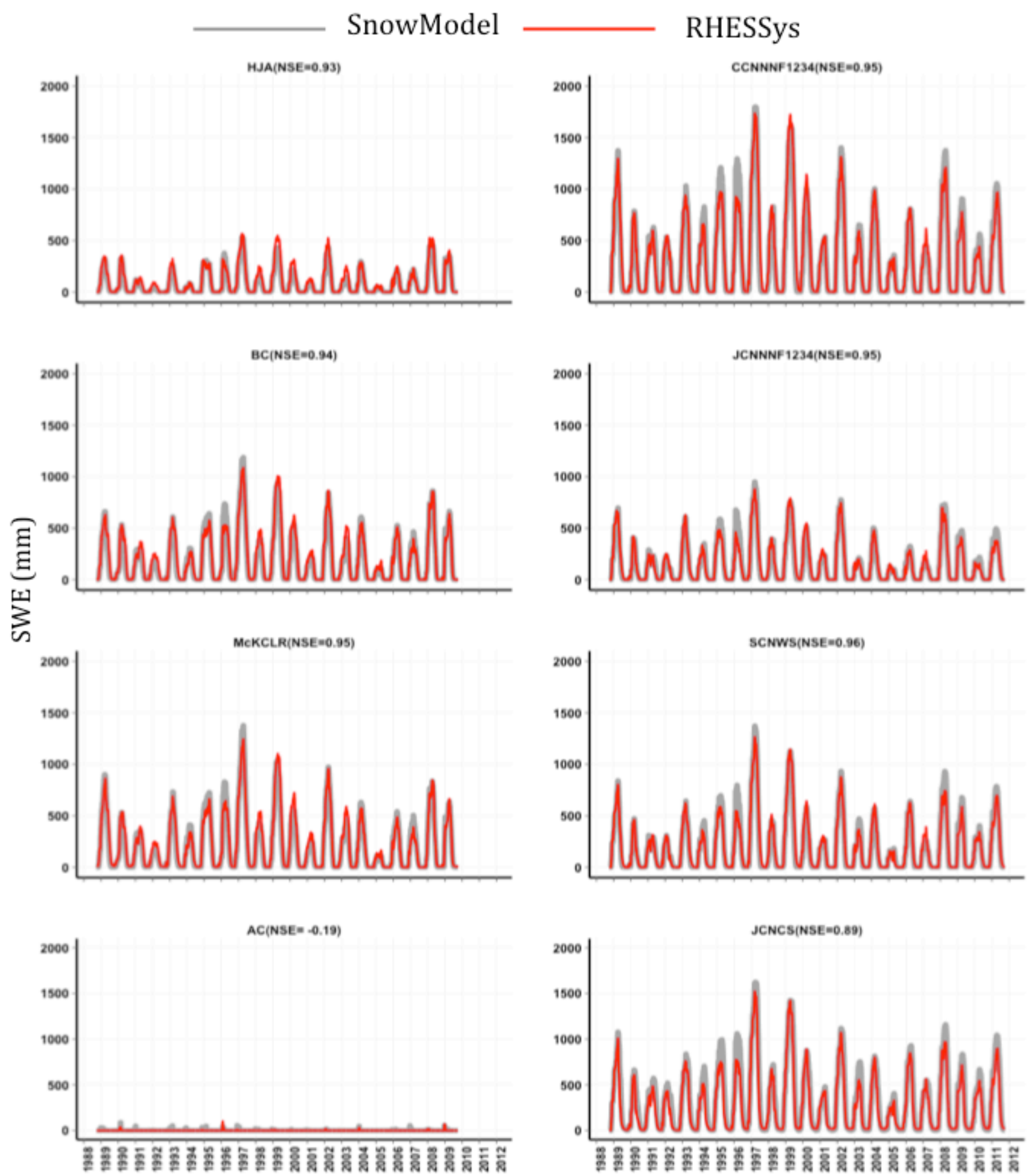

Figure 14. Comparisons of average daily snow water equivalent (SWE) simulated by the SnowModel and RHESSys across the eight watersheds

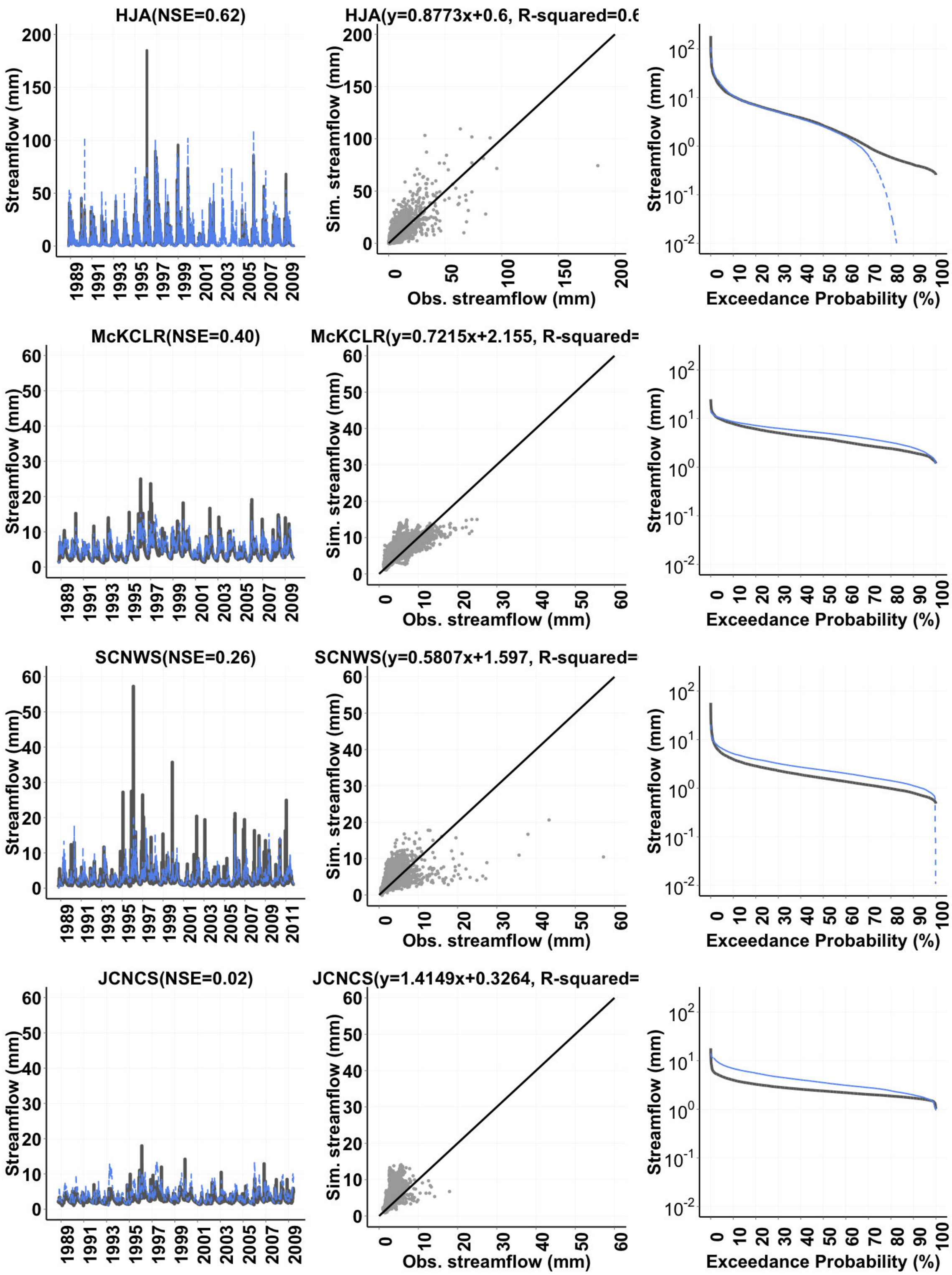

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Figure 15. RHESSys model performance in simulating daily streamflow across all the four (east side: SCNWS, JCNCS; west-side: HJA, McKCLR) calibration watersheds. Please note the difference in y-axis scale.

Comparisons of annual maximum peak flows showed slightly different pattern (Figure 16). Except for the few extreme years (e.g. 1996 rain on snow flood) observed and simulated annual maximum peak flows followed 1:1 line. However, there are some discrepancies among the watersheds. For example, annual maximum peak flows are largely over-predicted in HJA and under-predicted in McKCLR and SCNWS. One of the challenges, in getting the magnitude of peak flows right is accurately simulating the rain on snow events. However, representing the physics around the rain on snow events within a watershed hydrology model is extremely difficult. Additionally, error in precipitation during the flood events can lead to a strong bias in peak flows. Except for the HJA, in-situ precipitation observations in these watersheds are limited. For this reason, we had to rely on gridded meteorological forcings as described earlier. These gridded products may be useful for simulating daily SWE but not peak flows. Since, most of the meteorological stations are located at lower elevations, a simple monthly lapse rate based spatial interpolation may not accurately capture the precipitation and temperature variability during the extreme events that drive large floods.

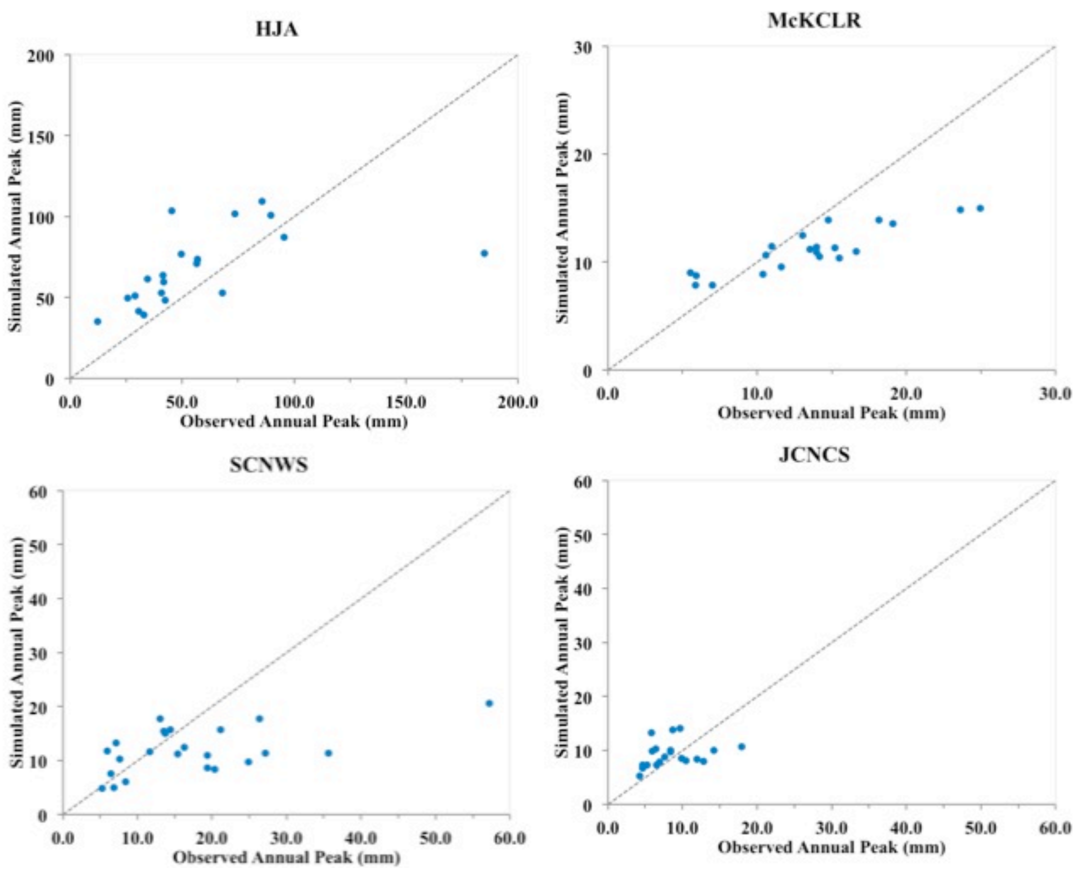

Figure 16. RHESSys model performance in simulating daily streamflow across all the four (east-side: SCNWS, JCNCS; west-side: HJA, McKCLR) calibration watersheds. Please note the difference in y-axis scale.

Effects of Future Climate Scenarios on Hydrographs

Warming scenarios would lead to winters with a greater proportion of rainfall vs. snowfall, a diminished snowmelt peak, and an earlier onset of the summer dry season

(Figure 17). However, the magnitude of flow increase or decrease will vary by the level of snowpack and stream type (runoff-dominated vs. spring-fed). Snowmelt peak will largely disappear with the 2^{o}C warming across all the watersheds. The greatest decline in snowmelt peak is in the BC followed by McKCLR. As expected, rain dominated AC showed no sensitivity to an increase in temperature. Except for the HJA and BC, increase in winter flows as a result of warming is within the range of historical snowmelt peaks. However, an increase of 10% precipitation combined with 4^{o}C increase in temperature may likely shift the winter flow above the spring snowmelt peaks. On east-side watersheds, there seems to be a shift in timing of higher flows than an increase in magnitude of flow. In terms of annual maximum peak flows, there was no difference between the +2^{o}C and +4^{o}C scenarios in west-side watersheds (Figure 18). On average, annual daily maximum peak flows are likely to increase between 0-50% under temperature scenarios (+2^{o}C and +4^{o}C) and as much as 55% under combined scenario (+4^{o}C +10% increase in precipitation). As compared to west-side watersheds, east-side watersheds show more sensitivity to continue to +4^{o}C scenario. This can be attributed to the slightly colder snowpacks on east- as compared to west-side.

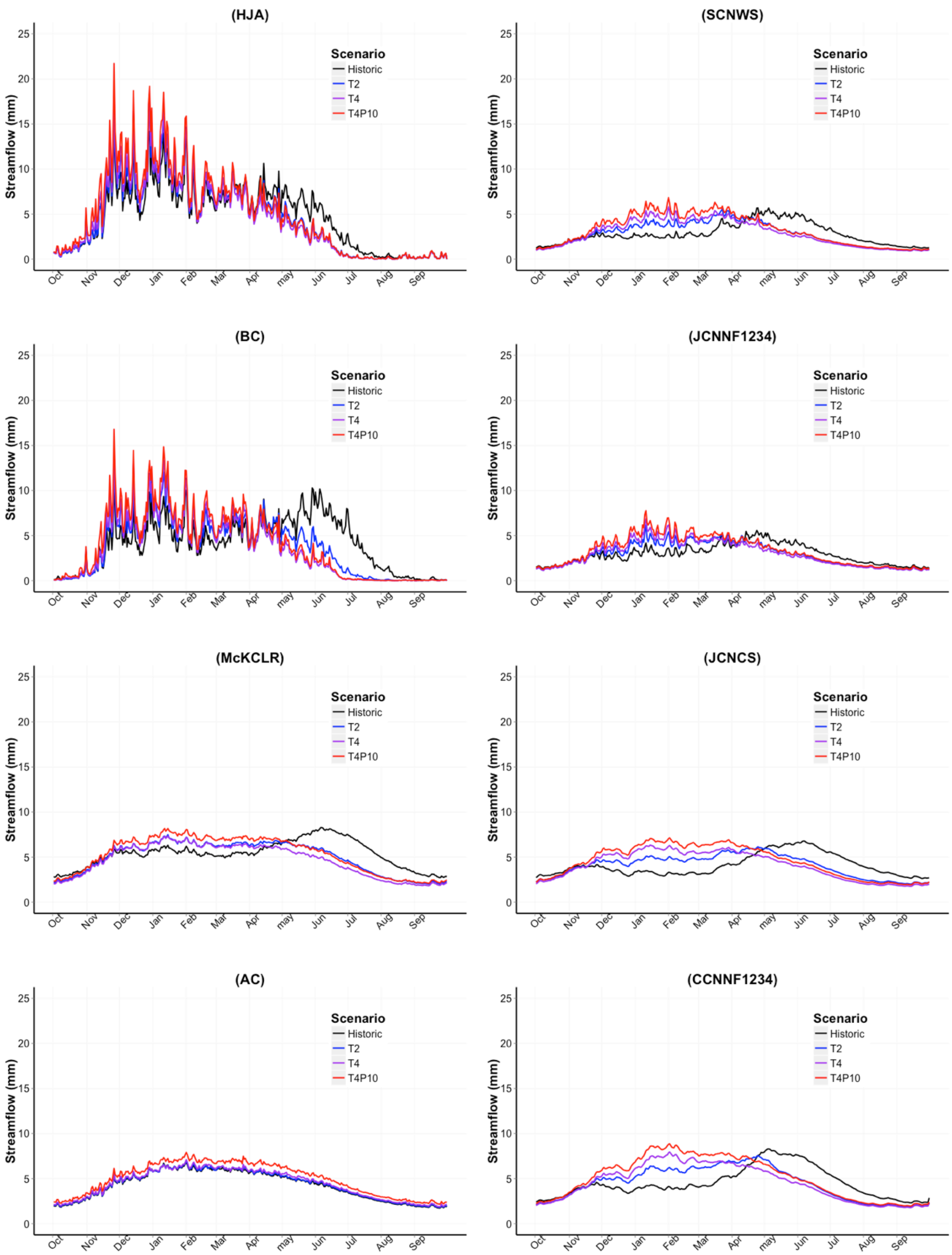

Figure 17. Effects of future warming (+2°C, +4°C) and change in precipitation (+10%) scenarios on annual hydrographs across the eight watersheds.

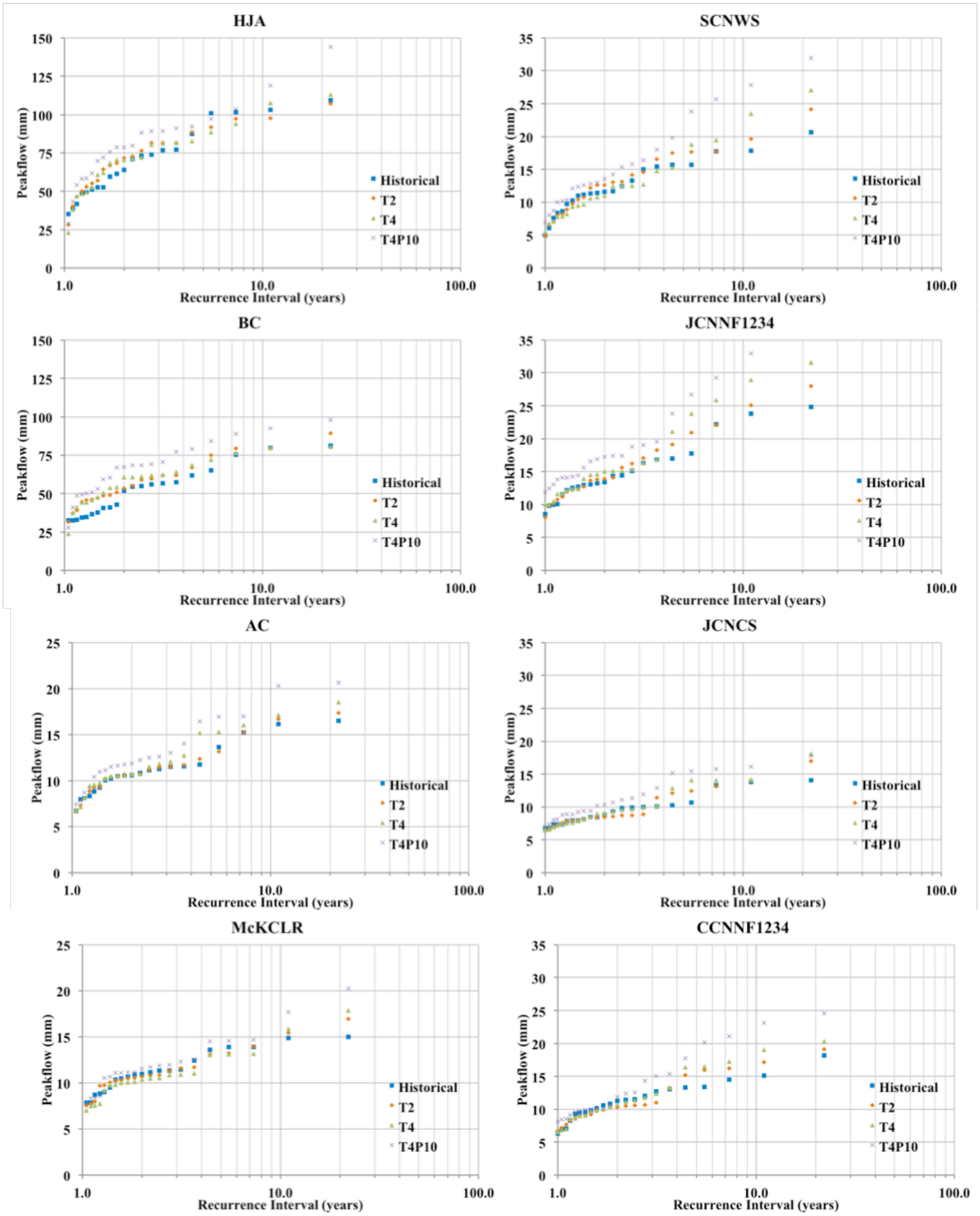

Figure 18. Changes in annual maximum peak flows under future temperature and precipitation scenarios.

d. Geomorphic Surveys and Sediment Transport Modeling

We examined changes in the timing and magnitude of bedload transport under modeled flow scenarios to identify which rivers draining the Cascades with different hydrologic regimes are most vulnerable to increased frequency of bedload transport. Such increases in the frequency or magnitude of gravel entrainment might lead to disturbance of fragile salmon or bull trout habitat. We calculated bedload transport rates using field measurements of surface sediment size, channel geometry, and channel slope along 14 reaches that included streams with a range of drainage areas and flow regimes (i.e., spring-fed and runoff dominated).

Channel Surveys

We surveyed four stream channels, which included a combination of spring-fed and surface-runoff channels located on both the wet and dry sides of the Cascades. We surveyed 3-4 reaches per stream. Following previous field-based sediment transport modeling studies in similar high gradient mountain environments (Mueller and Pitlick, 2005; Zimmermann and Church, 2010), each reach-level survey with a total station included the following measurements:

- 4 detailed cross sections surveyed across straight, riffle sections with little to no wood or vegetation and included water surface elevations and bankfull channel elevations
- Wolman pebble counts of the bed surface at each cross section (100 stones)
- Longitudinal water surface (both banks) and thalweg elevations with at least ½ active channel width, along with field notes of unit type at each point (e.g., pool, riffle, step, presence of wood, etc.)
- Limited pebble counts of distinct textural patch within the reach
- Limited measures of in-channel wood diameter, submergence, and orientation
- Measure flow discharge at each reach

Sediment Transport Modeling

We used modeled output hydrographs and data from field surveys to model daily sediment transport rate using the Wilcock and Crowe (2003) transport relation implemented with the Bedload Assessment in Gravel-bedded Streams (BAGS) tool. Wilcock and Crowe (2003) is a surface-based transport equation that accounts for the non-linear effect of sand content on gravel transport and includes a hiding function. We used a 1D modeling approach rather than the previously proposed 2D morphodynamic model because a 1D approach is a far more realistic undertaking for managers interested in similar questions to our own, there's a precedence for using 1D models which have been rigorously implemented numerous times in the literature and in field investigations, and because the input data required to accurately run a 2D morphodynamic model were prohibitive given our timeline and budget.

The foundation of the transport modeling was data calculated from the field survey. We used channel cross-section topographies, grain size distributions, manning roughness values, and reach slopes from the survey data to parameterize the model in BAGS. Our results are based on the transport relation developed by Wilcock and Crowe (2003) because that model more accurately represents transport dynamics when sand is present in the streambed compared to Parker (1990), which is another widely-used surface-based relation for gravel-bedded river but does not include the sand fraction. Due to modeling constraints, we were only able to run the sediment transport model for west-side sites, consequently our analysis below includes only Anderson Creek (spring-fed) and Boulder Creek (surface-runoff).

Results

Our findings suggest that both spring-fed and surface-runoff streams are vulnerable to predicted changes in the flow regime, but in different ways. First, plots of discharge (Q_{water}) and sediment transport rate (Q_{sed}) based on Wilcock Crowe (2003) and the baseline (no warming) scenario for water year 1990 show that the hydrograph and transport rate are more uniform in spring-fed systems compared to surface-runoff systems (Figures 19-20). Low levels of transport occur year-round in the spring-fed channel, which is notably different from the surface-runoff channel where transport rate is near zero for about 1/3 of the year but increases by five orders of magnitude during the wet season.

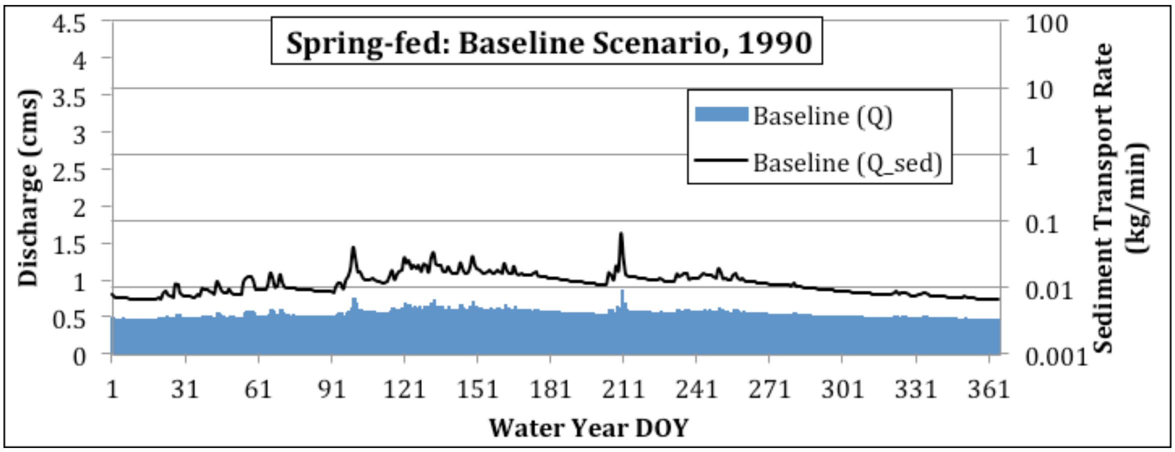

Figure 19. Discharge (Q_{water}) and sediment transport rate (Q_{sed}) based on Wilcock Crowe (2003) on Anderson Creek, a spring-fed system, for water year 1990.

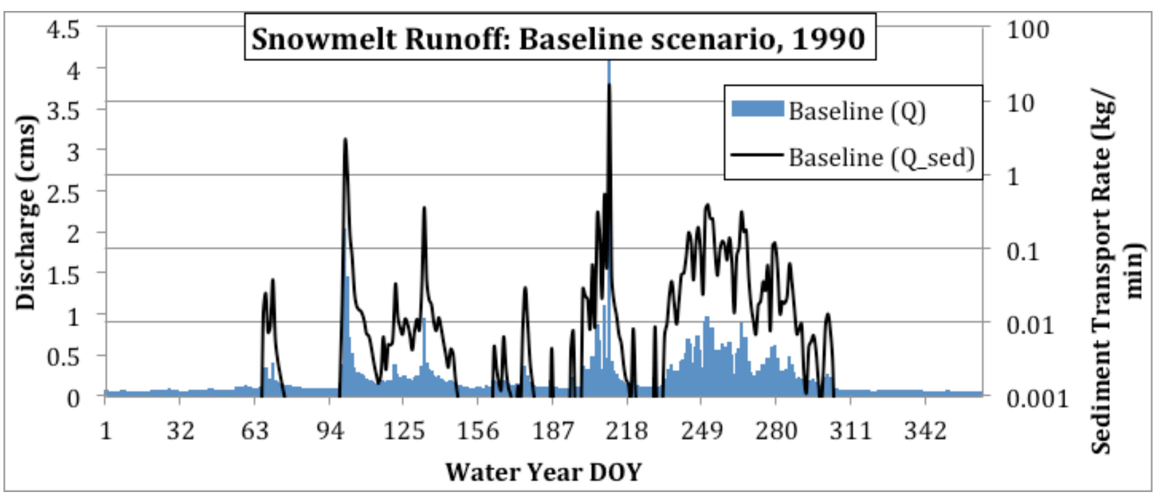

Figure 20. Discharge (Q_{water}) and sediment transport rate (Q_{sed}) based on Wilcock Crowe (2003) on Boulder Creek, a surface-runoff system, for water year 1990.

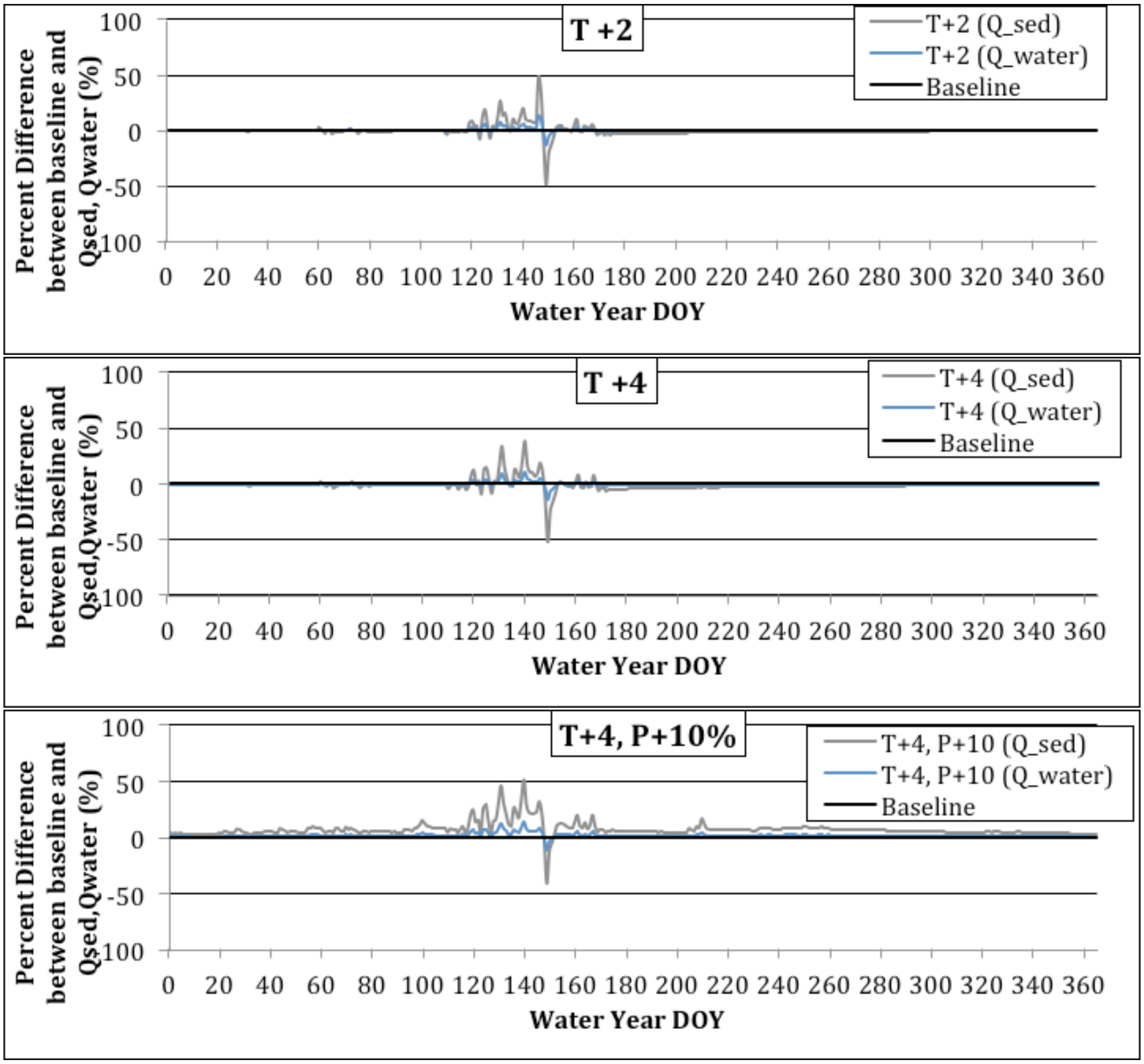

Figure 21. Plots of percent difference in water discharge (blue line) and sediment transport rate (gray line) for each warming scenario for Anderson Creek, a spring-fed system, during water year 1990.

We found that under all warming scenarios, daily deviations from baseline in discharge and consequently sediment transport rate are more frequent and more pronounced in the surface-runoff system (Figure 21-22). The spring-fed system will experience larger peak flows (up to 16% higher) and an increase in the number of days in a year with flows greater than historical flows (at least 25% greater) by 67 days. In comparison, changes in the surface-runoff systems will be even larger, the highest flows will increase up to 85% and the number of days in a year with flows greater than historical flows (at least 25% greater) will increase by 135 days. Consequently, daily sediment transport rate in the surface-runoff system will be up to 200% different from baseline under warming scenarios compared to only about 60% different in the spring-fed system. Deviations from baseline in the snowmelt channel also span the entire year rather than just the winter flood season.

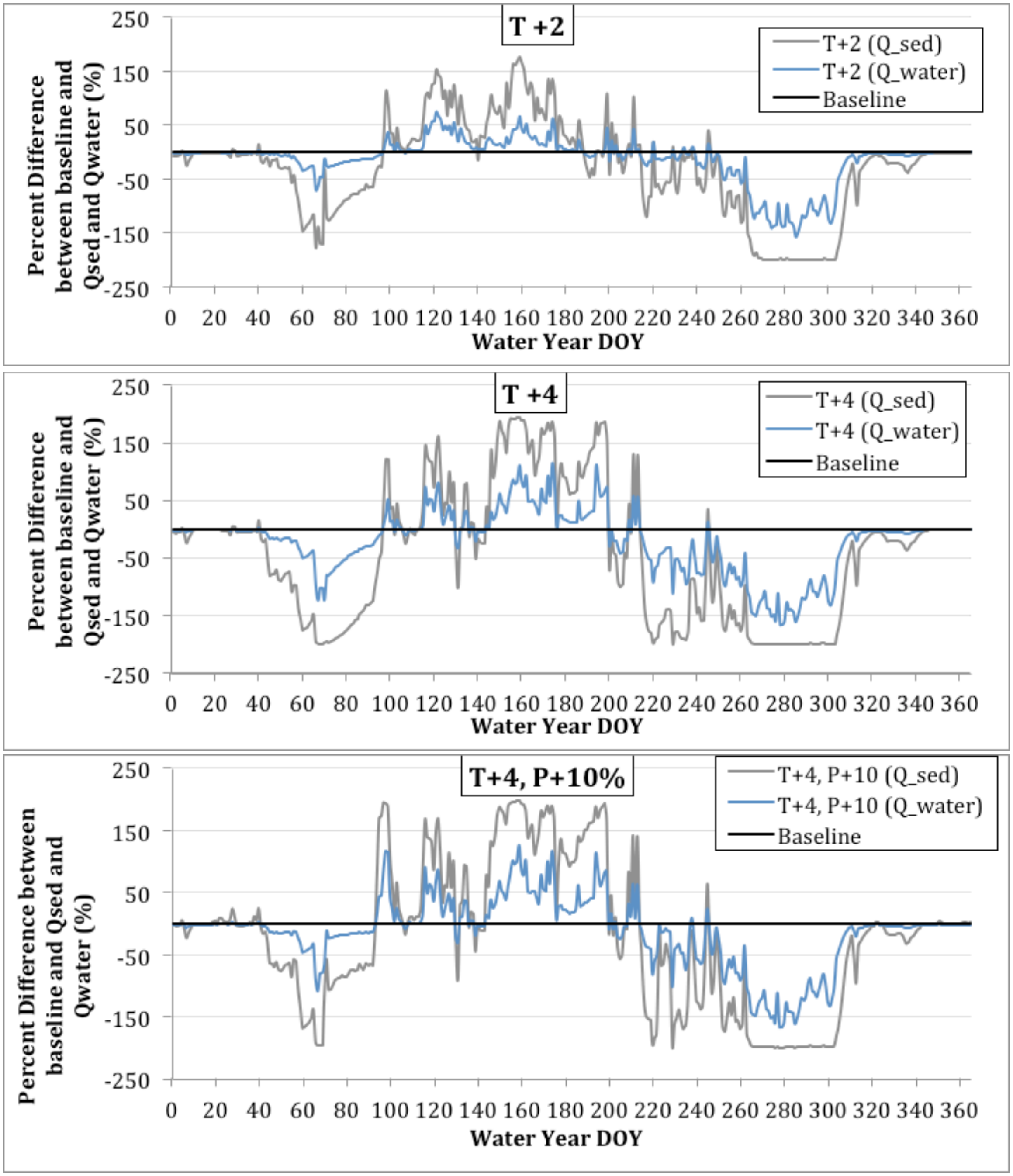

Figure 22. Plots of percent difference in water discharge (blue line) and sediment transport rate (gray line) for each warming scenario for Boulder Creek, a surface-runoff system, during water year 1990.

In comparing the entire period of record, we found that even though total runoff declined in the snowmelt channel, transport rate increased much more compared to the spring-fed channel (Figure 23-24, Table 2). While discharge declined 2.8 to 12.6% in the snowmelt channel, total discharge actually increased by +0.6 to 5.0% in the spring-fed channel compared to baseline. Transport rate increased in both systems, but increased by a higher percentage in the surface-runoff system (33.7-124.6%) compared to the spring-fed channel (32.0-118.4%).

Even though total runoff decreased in the snowmelt channel, transport rate went up by a much larger margin because the frequency of peak flows, which transport the majority of the sediment, increased. Therefore, changes to the hydrologic system do not result in an equivalent change in transport capacity and changes to the distribution of flow are as important as changes to the volume of flow when predicting transport capacity response.

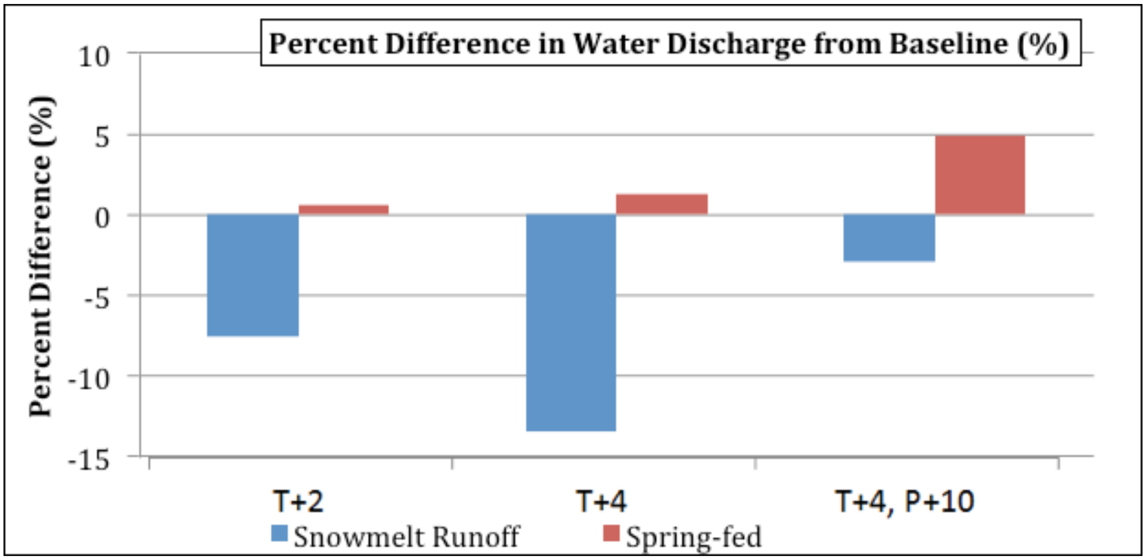

Figure 23. Percent difference in water discharge from baseline in each system for each scenario and the entire period of record (1988-2009).

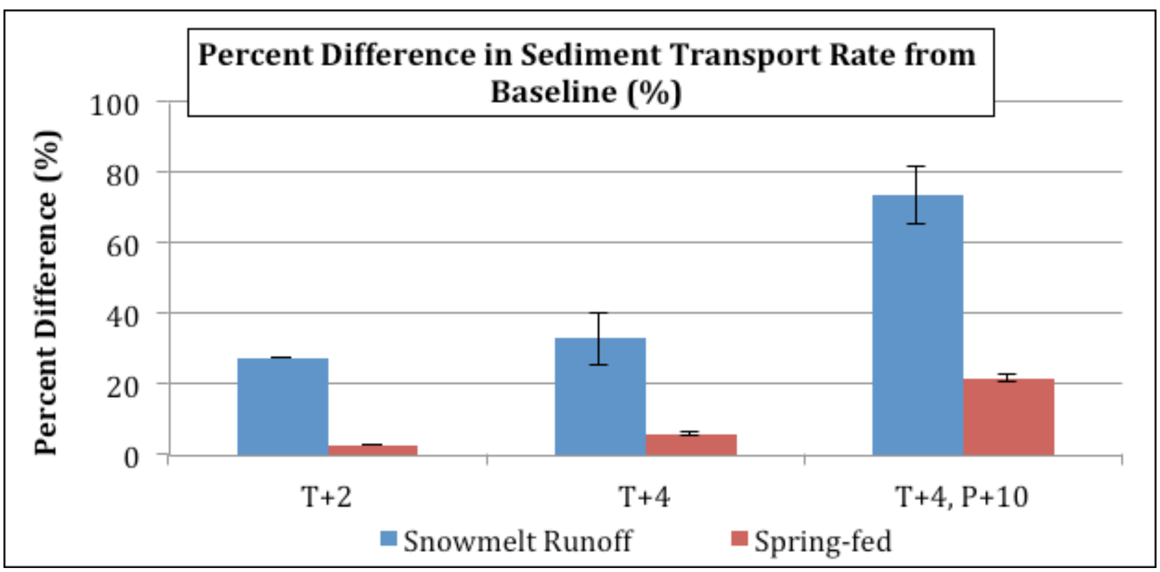

Figure 24. Percent difference in sediment transport rate from baseline in each system for each scenario and the entire period of record (1988-2009).

Table 2. Percent differences in water and sediment transport rate for Anderson Creek (spring-fed) and Boulder Creek (surface-runoff), including total annual discharge and annual sediment load normalized by drainage area for the entire period of record (1988-2009).

Spring-fed				
	Baseline	+2°C	+4°C	+4°C, +10% Precip
% Difference in Water Discharge from Baseline	0.0	0.6	1.3	4.9
Annual Discharge (m)	17.6	17.7	17.9	18.5
% Difference in Transport Rate from Baseline	0	2.6±0.4	5.6±0.8	21.5±3.2
Annual Sediment Load (kg/m2)	1.9E-03 ±2.7E-03	1.9E-03 ±2.8E-03	2.0E-03 ±2.9E-03	2.3E-03 ±3.4E-03

Snowmelt Runoff				
	Baseline	+2°C	+4°C	+4°C, +10% Precip
% Difference in Water Discharge from Baseline	0.0	-7.6	-13.4	-2.9
Annual Discharge (m)	0.2	0.2	0.2	0.2
% Difference in Transport Rate from Baseline	0	27.3±7.2	33.0±8.1	73.5±14.1
Annual Sediment Load (kg/m2)	1.4E-02 ±1.7E-02	1.9E-02 ±2.2E-02	2.0E-02 ±2.4E-02	3.2E-02 ±3.7E-02

Our sediment transport model results show that larger and more frequent high flows correspond to increased sediment transport rates, especially in the surface-runoff channel. Under such peak flow scenarios, this could lead to a more mobile streambed where gravels dominate. This would have significant impacts on salmonid species. These impacts and the management implications are discussed in the following section.

7. Synthesis, Conclusions, Recommendations, and "Next Steps"

Our results indicate that headwater catchments in the Oregon Cascades (particularly those in the 1000-1300m elevation range) will experience a significant shift from snowfall to rainfall (as much as 70%) for just a 2°C warming and even greater impacts for a 4°C warming. This shift in precipitation phase when combined with increased snowmelt rates, will lead to enhanced winter peak flows both in terms of overall flow magnitude as well as frequency of high flows. The diminished snowpacks will melt earlier in the spring, leading to a longer dry season and reduced flows during the summer. Our model shows that the initial 2°C warming will have the greatest impact on streamflow regimes (wetter winter, minimal snowmelt peak, and earlier summer drought) across all the watersheds. There are enhanced peak flows for all watersheds under both the 2°C and 4°C warming scenarios but the magnitude of increase varies by the amount of snow in the watershed and the overall groundwater contribution. For spring-fed systems, annual daily maximum peak flows could increase by as much as 55% when increased temperatures of 2°C or 4°C are combined with a 10% increase in precipitation. These are still within the historic range of spring snowmelt peaks though the spring-fed system will experience an increase in the number of days in a year with flows greater than mean historical flows (at least 25% greater) by 67 days. In comparison, changes in the snowmelt-dominated surface runoff systems will be even larger, the highest flows will increase up to 85% and the number of days in a year with flows greater historical flows (at least 25% greater) will increase by 135 days.

Consequently, under the climate change scenarios the daily sediment transport rate in the runoff-dominated watersheds will be up enhanced by up to 200% compared with baseline levels. The daily sediment transport rate in the spring-fed watersheds will be enhanced by about 60%. Also, runoff-dominated watersheds show deviations from baseline sediment transport that span the entire year rather than just the winter high flow season.

a. Recommendations and Next Steps for Future Work

While our models simulate significant impacts on snowpack dynamics, runoff patterns, and sediment transport in both spring-fed and runoff-dominated stream systems, it remains unclear how changes in magnitude and frequency of sediment transport will impact overall bed stability and channel morphology, and in turn how changes to the hydrograph will impact in-channel habitat. Findings based on our modeling efforts were able to address several key management questions but as is always the case, answers can lead to new and more complex questions. We note that there would be value in extending these modeling results to better understand and quantify how changes in winter peak flows modify channel stability from upstream- to downstream reaches, how changes in winter peak flows combined with changing stream temperature might affect aquatic habitat and fish life histories in both stream-fed and surface-runoff dominated watersheds.

8. Management Applications and Products

a. Management Implications

There are a number of management implications from our study including implications, mainly focusing on fish habitat. For instance, larger and more frequent high flows that correspond to increased sediment transport rates, especially in the surface-runoff channel, could lead to a more mobile stream bed where gravels dominate. Chinook have evolved to incubate eggs during winter low flows, which minimizes the risk of scour, so that juveniles emerge before the spring snowmelt pulse (Quinn, 2005). Therefore, more frequent bed-mobilizing flows during late fall and early winter could put eggs of autumn-spawning fish, like Chinook salmon, at risk of scour. In the Pacific Northwest, egg burial depths for Chum salmon are very close to scour depths, so that small changes in scour frequency could lead to a dramatic reduction in survival (Montgomery et al., 1996).

One study found that surface coarsening associated with redds creation reduced bed mobility, so a reduction in spawning due to changes in the flow regime could be further exacerbated by a more mobile bed caused by fewer redds nests (Montgomery et al., 1996). Furthermore, smaller-bodied fish, such as bull trout, have shallower egg burial depths and are therefore at increased risk of scour during their incubation period (Goode et al., 2013). Streambed mobility varies spatially over different flows and our study only looked at reach-scale transport, so we can’t comment directly on sub-reach scale (i.e., redds-scale) changes in mobility. However, several studies at the sub-reach scale found that unconfined channels characterized by greater accommodation space and habitat complexity (e.g., large wood), which provides refugia during high flows, experienced less bed scour and habitat disturbance during high flow events (Shellberg et al., 2010; Goode et al., 2013; McKean and Tonina, 2013). One study that looked at sub-meter changes in bed mobility under climate warming found that in an unconfined channel increased winter flows were accommodated by side-channels and the floodplain; consequently they predicted mobility in less than 2% of the streambed surface and only limited risk of habitat scour (McKean and Tonina, 2013). The previous study was based on data from the Salmon River in Idaho, a larger and lower gradient river compared to our Cascade study sites, so the question becomes: is there sufficient overbank accommodation space in our Cascades streams to act as a ‘stress relief valve’ and effectively reduce the risk of bed scour, despite increases in sediment mobilizing flow with warming? The answer to this question likely relates back to the morphology of each channel type.

The surface-runoff channel is characterized as a high-gradient, high-energy system with steep, V-shaped banks. Consequently, most of the energy during high flows is concentrated in the channel and is borne by step-pool structures and large boulders that protrude into the flow. With little floodplain or side-channel accommodation space, steep surface-runoff channels like Boulder Creek could be at high risk of scour with more frequent peak flow events. But since these systems are high energy, they already lack suitable habitat and changes to the flow regime under warming likely will not result in a significant decrease in habitat. For example, an aquatic habitat survey conducted by the forest service in 1997 only found cutthroat trout in the first river mile of Boulder Creek because a 6ft waterfall prevented fish passage farther upstream (Ray Rivera, personal communication).

In comparison, the spring-fed stream, Anderson Creek, historically provides an abundance of suitable habitat for bull trout. For example, in 2007 a redds survey by the US Forest service found 58 redds nests in Anderson Creek, compared to only 15 nests in nearby Olallie Creek (Ray Rivera, personal communication). The spring-fed channel is lower gradient and has more accommodation space both within the channel and on the near-flat floodplains. Increases in peak winter flows may therefore spill onto the floodplain and frequent in-channel wood structures could help reduce flow velocities and protect the streambed from scour, resulting in more limited risk to redds nests compared to the surface-runoff channel.

Based on our analysis and findings from previous studies, we predict that aquatic habitat in spring-fed systems will be most vulnerable to changes in the flow regime with warming because spring-fed streams already provide productive spawning habitat and since the bed is mobile most of the year, changes in the frequency and magnitude of bedload transport could put redds at greater risk of scour.

b. Potential Management Impacts

The results and conclusions of this research are likely to benefit our stakeholders in terms of water resources management, reservoir management, and aquatic habitat management. Below, we list three management concerns/research needs from our stakeholder/collaborators that they provided in the proposal phase of our project and briefly illustrate how our results addressed these concerns.

1. The Eugene Water and Electric Board "relies on the McKenzie River as a sole source of drinking water for over 200,000 people and for hydroelectric power generation from our Leaburg, Walterville, Carmen-Smith, and Trailbridge projects, [and] we are very interested in how winter peak flows will impact river and channel dynamics, aquatic habitat, dam operations and water quality."[1] Our research directly addressed this concern and we modeled and characterized winter peak flows for the McKenzie River Basin, which contains all four of the hydropower stations. As described earlier, winter peak flows and sediment transport will substantially increase in all watersheds especially in those

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[1] Letter from Karl Morgenstern (EWEB Drinking Water Source Protection Program Coordinator; 20 April 2012).

watersheds where snowmelt is substantial and where the geologic setting leads to surface runoff.
2. The USDA Forest Service/Pacific Northwest Research Station has expressed that our studies of winter peak flows and sediment transport address “a heretofore underexplored but potentially vital linkage between diminishing snowpack, changing streamflow regimes, and habitat for listed T&E species such as bull trout and Chinook salmon. [The] focus on both the eastern and western drainages of the Cascades means that results from their work will be broadly applicable to a wide range of National forests, including the Willamette, Deschutes, Mt. Hood, Rogue River, Gifford-Pinchot, Klamath, and Winema, among others.”[2] Again, our results bear out the critical importance of understanding both climate and geologic setting when predicting potential impacts on watersheds and critical habitat for threatened and endangered species. As previously discussed, salmonid habitat conditions are likely to be modified when winter peak flows increase though the impacts will vary depending on watershed geology and amount of snow cover.
3. In email discussions with our collaborator Dr. Jason Dunham, he indicated that increased peak flows (and thus increases in flashy flows) could modify the life histories of existing fish species as well as the overall species mix. “Work in the Deschutes (Zimmerman and Reeves) and nearby basins suggests that expression of steelhead life histories is tied to more flashy flow regimes and greater overall stream size (Mills et al. 2012). Maturation of fish in freshwater (e.g., becoming rainbow trout) is strongly tied to colder water, as seen currently in both the Deschutes and McKenzie (McMillan et al. 2012). In fact the McKenzie could conceivably switch from an exclusively native population of rainbow trout to a mixed life history with steelhead (as we see in other warmer and less stable Willamette streams) as climate impacts are realized.”[3] While a study of impacts on fish species was outside the scope of our project, we worked with Dr. Dunham to select watersheds where there were ongoing studies on bull trout and Chinook salmon. Specifically, we included Anderson, Ollalie, and Boulder creeks in our study because of the extensive studies in those watersheds. Our findings for these and other watersheds suggest increased winter peak flows and sediment transport impacts for these watersheds. Our model results predict a shift toward a more flashy flow regime for both spring-fed and surface-runoff systems but especially so for the latter. As described earlier, the peak flows and ensuing sediment transport are likely to negatively impact redds and overall fish spawning habitat.

c. Knowledge-to-Action Network

We implemented a knowledge-to-action approach for dialog and effective information transfer to ensure that our research is relevant and useful to planning and decision-making. In this semi-formal process we convened scientists, managers, and decision makers at all stages of the process to communicate stakeholder information needs and scientific goals, identify the type and timing of information that is required, and to

[2] Letter from Brian Staab (USDA/Forest Service Regional Hydrologist; 24 April 2012)
[3] Email from Jason Dunham (USGS, Aquatic Ecologist; 12 March 2012)

consider appropriate visualization tools for effective information transfer. Stakeholder information is included in Table 3.

Table 3. List of stakeholders and collaborators.

Name	**Agency**	**Title**	**Role**
Jason Dunham	USGS-Forest and Rangeland Ecosystem Science Center	Supervisory Research Aquatic Ecologist	Collaborator/Stakeholder
Brian Staab	USFS-Pacific Northwest Research Station	Regional Hydrologist	Stakeholder
Christina Tague	UCSB-Bren School of Environmental Science and Management	Associate Professor	Collaborator
Marshall Gannett	USGS-Oregon Water Science Center	Hydrologist	Stakeholder
Karl Morgenstern	Eugene Water and Electric Board	Supervisor, Drinking Water Source Protection	Stakeholder
Nik Zymonas	Oregon Department of Fish and Wildlife	Project Leader	Stakeholder

The project's modeling approach and the desired outcomes were discussed and agreed upon at our initial half-day workshop in April 2013. Action items were further discussed through informal follow-up email and conversations. We discussed our 1-year progress at a follow-on workshop in April 2014 and covered final plans for modeling and information transfer. Although this project has ended, we continue to maintain close ties with our stakeholders and collaborators. This project has further strengthened our relationships to stakeholders and it continues to bear fruit in terms of new applied research ideas (in progress).

Discussions with stakeholders also covered the desired functionality for our information visualization tool (Figure 25). Although we ran out of time to update this tool prior to project completion, we intend to incorporate our model results into the visualization tool using student efforts (through GEO 460, Multimedia Cartography) in 2015.

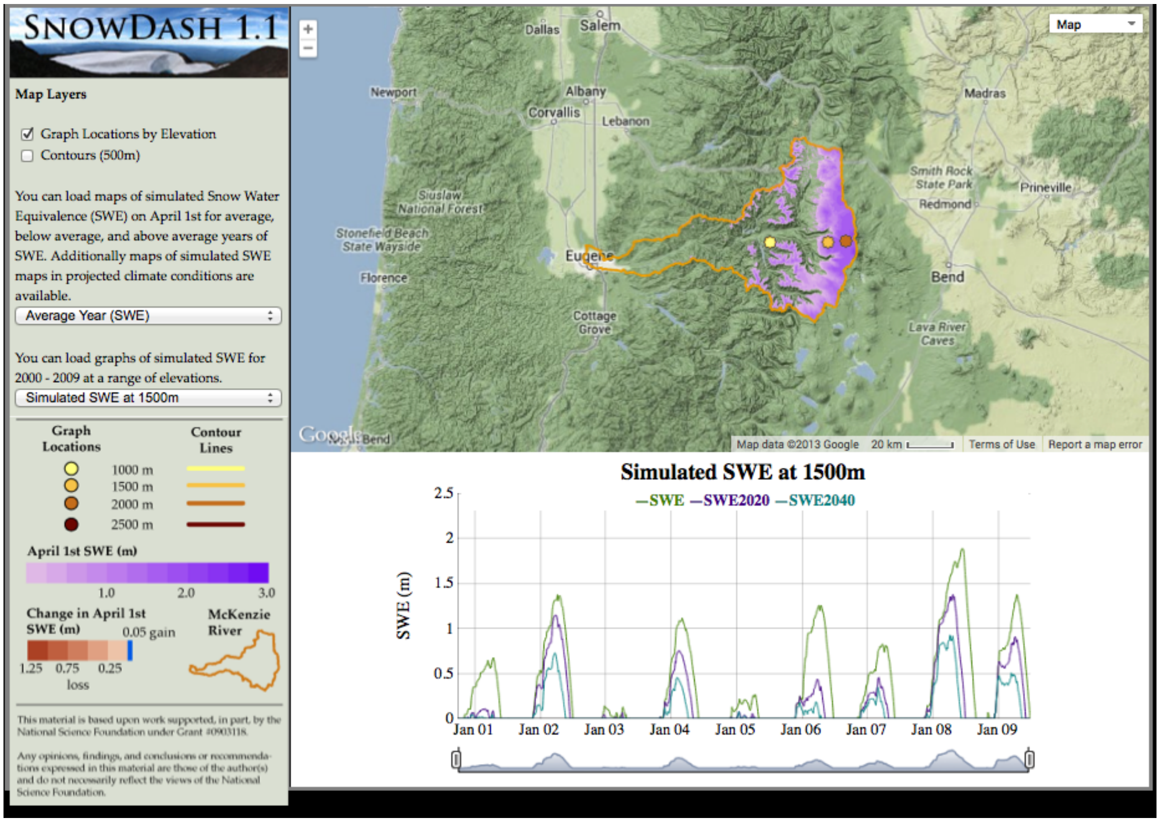

Figure 25. SnowDash visualization for the McKenzie Basin (Sproles, 2012). This project will add additionally functionality to this product, and expand the geographic scope to include a portion of the Deschutes basin. [http://www.science.oregonstate.edu/~sprolese/snowdash/snowdash.html.](http://www.science.oregonstate.edu/~sprolese/snowdash/snowdash.html)

9. Outreach:

a. Publications

- Cooper, M. G., "Modeling Snow in a Data Sparse Region", MS Thesis in preparation, expected completion: winter 2015.
- Cooper, M. G., and A. W. Nolin, "Modeling snow in a data sparse region: Bias correction improves results", (manuscript in preparation for Water Resources Research)
- Safeeq, M. et al. "Climate change and enhanced peak flows in the Oregon Cascades" , (manuscript in preparation for Water Resources Research)
- Hempel, L. Enhanced flows increase sediment transport, thesis chapter in preparation.

b. Presentations

- *Safeeq 11/14/12 "Climate change and peak flows: Knowledge-to-action to help managers address impacts on streamflow dynamics and aquatic habitat" Bren School, UC-Santa Barbara, California.*
- *Grant 2/14/13 "The Ultimate Hydrologic Sponge: how the plumbing system of the Cascades controls streamflow and response to climate change in the Willamette Basin" Calapooia Watershed Council, Brownsville, Oregon*
- *Cooper, Hempel 2/28/13 "Snow and Streamflow in the Central Oregon Cascades" Hydrophiles Brownbag Presentation, Corvallis, Oregon.*
- *Nolin 3/19/13 "Waning Winters and the Interconnected Effects of Snow and Wildfire" OSU Cascades Science Pub, Sisters, Oregon.*
- *Grant 4/11/13 "The Ultimate Hydrologic Sponge: How geology and climate define Willamette River streamflow, now and in the future" University of Oregon, Eugene, Oregon.*
- *Safeeq 4/2/13 "Streamflow Sensitivity to Climate Change in the Willamette River Basin", Halsey High School, Oregon.*
- *Grant 6/20/12 "The Ultimate Hydrologic Sponge: how the plumbing system of the Cascades controls streamflow and response to climate change in the Willamette (and Clackamas) Basins." Clackamas Watershed Council, Clackamas, Oregon*
- *Hempel 8/15/13 "Hydrology and channel hydraulics on headwater streams of the Central Oregon Cascades", Summer Institute for Earth Surface Dynamics, Minneapolis, MN.*
- *Cooper 9/5/13 "Climate Change and Peak Flows: Modeling Snow in a Data-Sparse Watershed" 4th Pacific Northwest Climate Science Conference, Portland, Oregon.*
- *Cooper 11/6/13 "Changing Snow in the Oregon Cascades: A Modeling Study of the McKenzie and Deschutes Headwater Catchments", American Water Resources Association Annual Conference, Portland, Oregon.*
- *Safeeq 11/5/13 "Mapping Streamflow Sensitivities to Climate Warming in the Pacific Northwest, USA", American Water Resources Association Annual Conference, Portland, Oregon.*

- *Cooper 12/12/13 "Climate Change and Peak Flows: Modeling Snow Across the East-West Divide of the Oregon Cascades for Future Peak-Flow Projections" American Geophysical Union Fall Meeting, San Francisco, California.*
- *Hempel 12/13/13 "A Comparison of Hydrology and Channel Hydraulics in Headwater Streams of the Central Oregon Cascades" AGU Fall Meeting, San Francisco, California.*
- *Grant 4/11/14 "From Volcanoes to Rivers: Co-evolution of hydrologic and geomorphic processes in a young volcanic arc" Bretz Club for Oregon Geomorphologists, Gresham Oregon.*
- *Grant 4/23/14 "An overview of climate change impacts on streamflow" BMAP, LaGrande, Oregon.*
- *Grant 5/14/14 "The Ultimate Hydrologic Sponge: how geology and climate define streamflows in the Willamette River basin" Dividing the Waters Resources, The National Judicial College, Reno, Nevada.*
- *Hempel, L., Grant, G., Lewis, S., Safeeq, M., 12/17/2014. "Change in Bedload Transport Frequency with Climate Warming in Gravel-bedded Streams of the Oregon Cascades". AGU Fall Meeting, San Francisco, California.*
- *Nolin, A. 9/10/2014. "Snow-Forest Interactions Along an Elevation Gradient in the Oregon Cascades: Implications for Forest Management", Pacific Northwest Climate Science Conference, Seattle, Washington.*
- *Cooper, M., Nolin, A., 9/9/2014. "Does Snowpack Sensitivity to Warming Temperature Differ Across the East/West Divide of the Cascade Mountains?," Pacific Northwest Climate Science Conference, Seattle, Washington.*
- *Safeeq M., Grant, G., Lewis, S., Nolin, A., Hempel, L., Cooper, M., and Tague, C.L., 12/18/2014. "Integrated snow and hydrology modeling for climate change impact assessment in Oregon Cascades", AGU Fall Meeting, San Francisco, California.*
- *Cooper, M., Nolin, A., 12/18/2014, "How does the representation of altitudinal variation of temperature in gridded forcing data affect modeled assessment of snow sensitivity to climate warming?," AGU Fall Meeting, San Francisco, California.*
- *Nolin, A. W., Roth, T., Gleason, K., and Cooper, M., 12/18/2014 "Differential Effects of Wildfire and Forest Harvest on Snow Hydrology in the Oregon Cascades" AGU Fall Meeting, San Francisco, California.*

c. Other Communications

- On April 9, 2013, a half-day digital workshop was convened with collaborators and stakeholders. An overview of the project and preliminary findings were presented by project personnel Nolin, Grant, Lewis, and Safeeq, and graduate students Hempel and Cooper. Participating in the discussion of project direction and desired outcomes were Jason Dunham (USGS), Christina Tague (UCSB via phone), Karl Morgenstern (EWEB) and Brian Staab (USFS via telecom). Marshall Gannett (USGS) was invited but unable to attend and was subsequently updated via email.
- Nolin, September 18, 2013, invited presentation to the CSC/LLC Executive Stakeholder Advisory Committee. Discussed the impact of changing climate on peak flows and potential changes in channel morphology and sediment mobilization in the Upper Deschutes and Upper McKenzie River Basins.

- Grant, Summer 2013, Willamette River Float trip (WW2100) with representatives from USACE, USGS, Meyer Memorial Trust, ODFW, UO, OSU, NOAA Fisheries. Discussed project scope and initial findings to initiate a dialogue with stakeholders regarding project design and potential application.
- Nolin, October 31, 2013 invited presentation to Doug Beard, Chief of USGS National Climate Change and Wildlife Science Center, at OSU. Presented overview of project and preliminary findings. Clarified that while the project will measure stream temperature at the small watersheds, and make inferences as to how changes in flow might impact temperature, modeling changes in stream temperature due to climate change is currently outside the scope of the project.
- Grant conducted regular (approximately monthly) conversations with collaborator and stakeholder Brian Staab, USFS Region 6 to more closely align the project products with the needs of forest managers preparing for climate change on National Forest Lands.
- On April 29, 2014, a half-day digital workshop was convened with collaborators and stakeholders. The Year 1 progress report was distributed in advance of the meeting, and preliminary findings were presented by project personnel Nolin, Grant, Lewis, and Safeeq, and graduate students Hempel and Cooper. Participating in the discussion of project direction and desired outcomes were Jason Dunham (USGS), Christina Tague (UCSB via conference phone), Karl Morgenstern (EWEB) and Brian Staab (USFS via video TeleConference), Marshall Gannett (USGS via conference phone) and Nik Zymonas (ODFW). Following the presentation, each participant was given the opportunity to give feedback and suggestions to the group.
- Our final project-related communication with our stakeholders will be a copy of this final report with email and informal meetings to follow.

References Cited:

Garcia, E. S., Tague, C.L., and Choate, J. S. (2013). Method of spatial temperature estimation influences ecohydrologic modeling in the Western Oregon cascades, Water Resources Research, 49, 1611–1624.

Garcia, E. S. and Tague, C. L. (2014). Climate regime and soil storage capacity interact to effect evapotranspiration in western United States mountain catchments, Hydrology and Earth System Sciences, 11, 2277-2319.

Goode, J. R., Buffington, J. M., Tonina, D., Isaak, D. J., Thurow, R. F., Wenger, S., Nagel, D., Luce, C., Tetzlaff, D., and Soulsby, C. (2013). Potential effects of climate change on streambed scour and risks to salmonid survival in snow-dominated mountain basins, Hydrological Processes, 27, 750-765.

Liston, G.E., and Elder, K. (2006). A Distributed Snow-Evolution Modeling System (SnowModel), Journal of Hydrometeorology, 7, 217-234.

Livneh, B., Rosenberg, E.A., Lin, C., Nijssen, B., Mishra, V., Andreadis, K.M., Maurer, E.P., and Lettenmaier, D.P. (2013). A Long-Term Hydrologically Based Dataset of Land Surface Fluxes and States for the Conterminous United States: Update and Extensions, Journal of Climate, 26, 9384–9392.

McKean, J., and D. Tonina (2013). Bed stability in unconfined gravel bed mountain streams: With implications for salmon spawning viability in future climates, Journal of Geophysical Research: Earth Surface, 118, 1227–1240.

Montgomery, D. R., Buffington, J. M., Peterson, N. P., Schuett-Hames, D., and Quinn, T. P. (1996). Stream-bed scour, egg burial depths, and the influence of salmonid spawning on bed surface mobility and embryo survival, Canadian Journal of Fisheries and Aquatic Sciences, 53, 1061-1070.

Mueller, E. R., Pitlick, J., and Nelson, J. M. (2005). Variation in the reference Shields stress for bed load transport in gravel-bed streams and rivers. Water Resources Research, 41.

Quinn, T. P. (2005). The Behavior and Ecology of Pacific Salmon and Trout. American Fisheries Society, Bethesda, MD, 378 pp.

Shellberg, J.G., Bolton, S.M., and Montgomery, D.R. (2010). Hydrogeomorphic effects on bedload scour in bull char (Salvelinus confluentus) spawning habitat, western Washington, USA, Canadian Journal of Fisheries and Aquatic Sciences, 67, 626-640.

Sproles, E. (2012). Watershed-scale modeling of snow water equivalent under present day and future climate scenarios, Corvallis, Oregon State University.

Tague, C. and Band, L. (2004). RHESSys: Regional Hydro-ecologic simulation system: An object-oriented approach to spatially distributed modeling of carbon, water and nutrient cycling, Earth Interactions, 8, 1-42.

Tague, C. and Grant, G. (2009). Groundwater dynamics mediate low flow response to global warming in snow-dominated alpine regions, Water Resources Research, 40, W04303, doi:10.1029/2003wr002629, 2004.

Tague, C., M. Farrell, G. Grant, J. Choate, and A. Jefferson (2008). Deep groundwater mediates streamflow response to climate warming in the Oregon Cascades, Climate Change, 86, 189–210.

Watanabe, S. Kanae, S., Seto, S., Yeh, P., Hirabayashi, Y., and Oki, T. (2012). Inter-comparison of bias-correction methods for monthly temperature and precipitation simulated by multiple climate models, Journal of Geophysical Research, 177, DOI:10.1029/2012JD018192.

Wilcock, P. R. and Crowe, J. C. (2003). Surface-based transport model for mixed-size sediment. Journal of Hydraulic Engineering, 129, 120-128.

Zimmermann, A., Church, M., and Hassan, M.A. (2010). Step-pool stability: Testing the jammed state hypothesis, Journal of Geophysical Research: Earth Surface, 115, doi: 10.1029/2009JF001365.